Metallurgy Department. Progress report for the period 1 January to 31 December 1979

Risø National Laboratory, Roskilde

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Risø National Laboratory, DK-4000 Roskilde, Denmark
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METALLURGY DEPARTMENT PROGRESS REPORT FOR THE PERIOD 1 JANUARY TO 31 DECEMBER 1979

Abstract. The activities of the Metallurgy Department at Risø during 1979 are described. The work is presented in four chapters: General Materials Research, Technology and Materials Development, Fuel Elements, Non-Destructive Testing. An article on Wingblades of Glass Fibre Reinforced Polyester for a 630 kW Windturbine is also included. Furthermore, a survey is given of the department's participation in international collaboration and of its activities within education and training. A list (with abstracts) of publications and lectures by the staff during 1979 is included.

INIS-descriptors: FUEL ELEMENTS, METALLURGY, NON-DESTRUCTIVE TESTING, RESEARCH PROGRAMS, RISOE NATIONAL LABORATORY.

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1. INTRODUCTION

The time schedule for the establishment of nuclear power in Denmark is still uncertain. Risø is therefore still at stand-by in this field but most of the nuclear programmes have to be carried on in order continuosly to ensure up-to-date knowledge. In the Metallurgy Department the nuclear work comprises projects within design, fabrication and testing of fuel elements, fracture mechanics studies in pressure vessel steels and nondestructive testing. The projects concentrate more and more on advanced problems, which in many cases are studied in collaboration with other parties in Europe and in the United States. An example of such programmes is the "Risø Fission Gas Project" in which the fission gas release in Zircaloy-UO_2 rods after high burn-up is studied. This programme is sponsored by 10 firms and organizations in Europe and abroad. Other examples are ramp testing of fuel pins, computer modelling of fuel pin performance, dynamic fracture mechanics studies on steel and acoustic emission investigations of welds.

With respect to alternative energy technology, a major effort was devoted to fibre reinforced plastics, which have been chosen as wing-blade material for two 600 kW wind turbines built by a group of electricity generating companies. Six wings with a length of 12 meters each have been mounted and are operating satisfactorily. The department has participated in the wing development including fabrication studies, small scale and semi-scale mechanical testing and non-destructive testing. This work is described in detail in this report under the title "Wingblades of glass fibre reinforced polyester for a 630 kW windturbine". The wingblades were manufactured by two Danish firms and a number of such blades have already been sold for export. Other energy projects include metal-hydrogen systems (e.g. for transportation and storage of energy) and high temperature ion conductors; the latter project is carried out in collaboration with a group of Danish and British laboratories under the auspices of EEC and the Ministry of Energy.

Work has been done under contract for industries and utilities in Denmark and abroad. Due to their proprietary nature, most of these activities are excluded from the present report. Among the major activities were fuel element development, where collaboration with the Elsinore Shipyard was continued, isotope analysis and post-irradiation examinations of full-scale power reactor fuel rods (Zr-UO_2 and Zr-UO_2-PuO_2).

Other work on contract was done on high temperature components for the chemical industry and on acoustic emission for non-destructive testing purposes. The corrosion aspects of high level waste disposal in salt domes were evaluated as part of an advising assistance from Risø to a waste management project sponsored by the Danish utilities. In this project salt from drillings in Jutland will be analyzed in the department. Further projects were centered on the development of materials and processes, in particular ceramics for measurement of oxygen potentials in combustion gases, sintering of nuclear ceramics, and brazing technology. In the field of neutron radiography standardization work was initiated and a neutron radiography working group sponsored by Euratom has been formed.

To support the technological programmes of the department a large effort was as usual devoted to fundamental problems e.g. radiation damage in metals, strength/structure relations in single-phase and two-phase metarials and structures in ceramics. A large part of the fundamental work is carried out in collaboration with universites and research laboratories in Denmark and abroad.

The department participated in international collaboration on specific research projects and also in a number of international projects and study groups under the auspices of the NEA, EEC and various Nordic organizations.

The planning was started for two international symposia to be held at Risø in 1980. The titles of these symposia are Recrystallization and Grain Growth of Multi-phase and Particle Containing Materials, Risø, 8-12 September 1980.

IAEA Specialist's Meeting on Pellet-Cladding Interaction in Water Reactors, Risø, 22-26 September 1980.

Educational activities were continued; students and post-graduates from Denmark and abroad studied in the department.

GENERAL MATERIALS RESEARCH

Additive strength contributions

The relationship between strength and structure of dispersion strengthened polycrystals was studied with Cu-Al_2O_3 as a model system. Below a strain of 0.03 dispersion strengthening in the polycrystals can be explained on the basis of theories for the yield stress and flow stress of dispersion strengthening single crystals. The grain boundary strengthening can be described by the Hall-Petch relation. A relation between the Hall-Petch slope and the particle spacing was derived and experimentally verified.

Cu-Al_2O_3 polycrystals for tension-compression testing were fabricated with a well-defined structure by plane strain - plane stress deformation of internally oxidized Cu-Al single crystals followed by recrystallization. The structure was examined by optical and electron microscopy.

Deformation of composites

The mean field model (MFM) for the effective thermoelastic and plastic deformation of multiphase composites was extended to reproduce Walpole's bounds for the elastic constants. The MFM and the self-consistent approximation were found to give compatible descriptions of the effect of fibre length on the elastic deformation of fibre composites. Walpole's formulation was combined with Levin's extension of Hill's method to obtain bounds for thermoelastic deformation. This new combination of theories was found to reproduce the MFM bounds for thermoelastic deformation. However, it cannot provide expressions bounding the new hardening effect (elastic mean stress) predicted by the MFM.

In collaboration with the Cavendish Laboratory and the Department of Metallurgy and Materials Science, Cambridge University,

UK, a two-phase model is being developed to explain measurements of hardening and Bauschinger effect in pure copper. The model represents pure copper as a composite in which thin sheets of a hard phase (dislocation tangles) are embedded in a softer (relatively dislocation-free) matrix. The transient softening is understood to be caused mainly by internal stresses. The absence of a large permanent softening is understood to result from dynamical plastic relaxation of the hard phase. When combined with the dislocation theory of pile-ups the two-phase model can provide a quantitative description of the forward and the reverse flow stress of pure copper.

Creep in fcc metals

When a creep-deformed material is annealed after creep, the dislocation density decreases faster during the first phase of annealing than expected from existing theories. A possible explanation of this deformation-enhanced recovery has been given in terms of dislocation theory, and an experimental study of the phenomenon has been initiated on Cu in order to test the model. Deformation-enhanced recovery of the dislocation network influences the creep rate, and the new recovery model is therefore being incorporated in a model for creep.

Fatigue phenomena in copper

Polycrystals of pure copper were cyclically deformed in tension-compression at constant low plastic strain amplitudes. The measurements provided further evidence for the plateau observed in plots of the saturation stress versus the plastic strain amplitude and they suggest that the saturation stress may depend on the strain-rate. The area fraction of persistent slip bands on the cyclically deformed polycrystals was measured and found to depend linearly on the plastic strain amplitude. The dislocation structures developed during the cyclic deformation were examined by transmission electron microscopy and clear

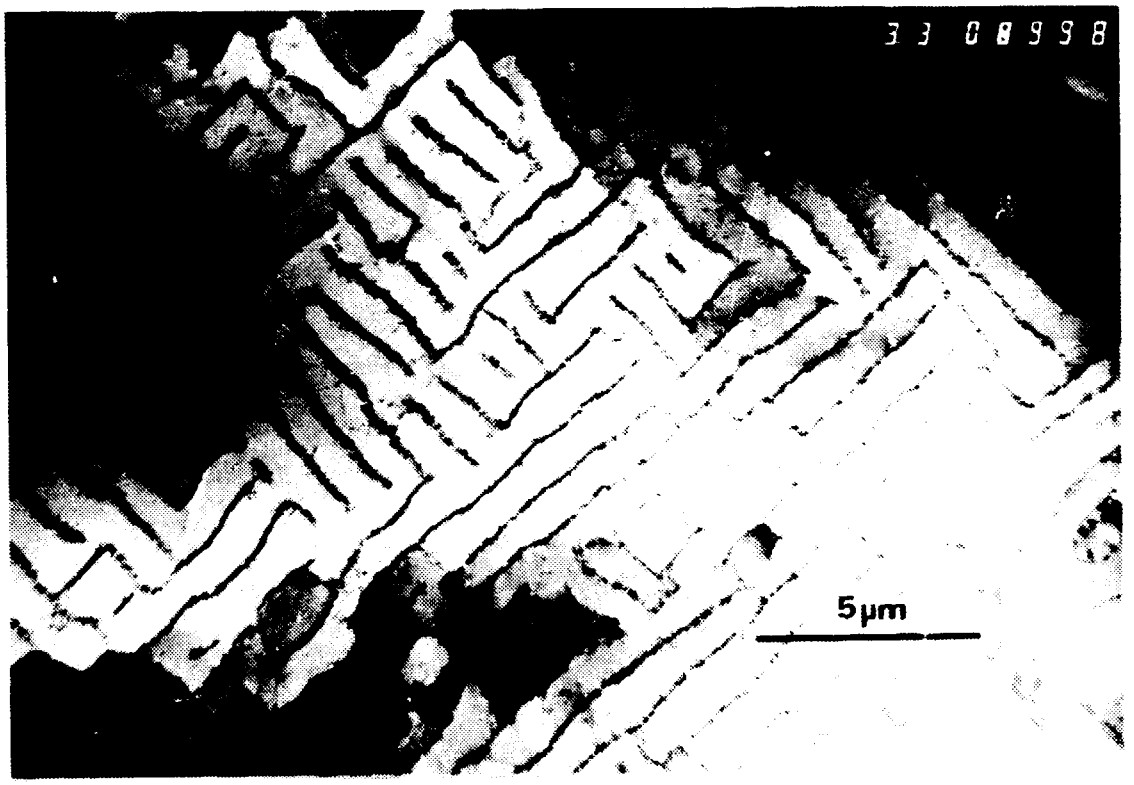

Fig. 1. Bulk dislocation structure in a copper polycrystal fatigued in tension-compression with a plastic strain amplitude of 2.33×10^{-3} at a frequency of 0.25 Hz. The relatively short dislocation walls are all approximately normal to <110> directions.

examples of a wall structure, a vein structure and a cell structure were found in bulk grains. An analysis of internal stresses was made and it was shown that persistent slip in the bulk wall structure can easily be elastically accomodated. Taken as a whole the experimental evidence suggests that a combination of the two-phase model, the Sachs model and Eshelby's theory of internal stresses may provide a realistic description of low-amplitude fatigue of polycrystals of copper.

Plastic deformation of polycrystals

In the Taylor model for the plastic deformation of polycrystals material continuity is maintained by a pattern of multiple slip in the individual grains. In each grain there is a range of combinations of slip systems available, determined by the lattice orientation in that particular grain, and not influenced

by the lattice orientations of the surrounding grains. The different slip system in the multiple slip patterns are considered qualitatively equivalent (no distinction between primary and secondary systems). The strain is supposed to be the same at all points in the material (equal to the external strain). There are a number of theoretical and experimental objections to the Taylor model in this formulation.

In the Sachs model one only considers slip on one slip system in each grain (the primary system), which means that no account is taken of the requirement of material continuity.

A suggested new model, combining the Taylor and the Sachs models, seems to be compatible with the experimental evidence available, and it does not give rise to theoretical problems. In the new model (referred to as "the modified Sachs model") primary slip is the initial event; the misfit produced by primary slip is then accounted for by slip on the secondary systems. The resulting slip pattern varies from point to point in the material - also with respect to the resulting strain. Thus, the slip

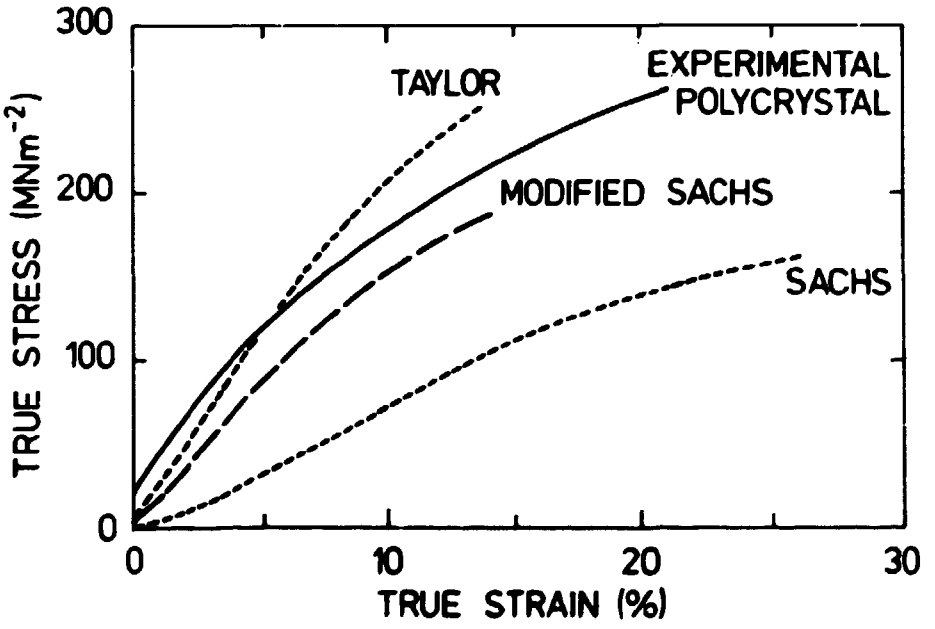

Fig. 2. Comparison of experimental stress/strain curve for polycrystal with curves derived from single crystal curves on the basis of the Taylor, the Sachs, and the modified Sachs model.

pattern derived from the new model agrees far better with experimental observations than that derived from the Taylor model. Polycrystal stress/strain curves derived from single-crystal curves on the basis of the new model agree far better with experimental curves than those derived on the basis of the Sachs model as shown in fig. 2.

Radiation damage in stainless steel

(in collaboration with the Metallurgy Division, AERE Harwell)

The study of radiation damage in laboratory made austenitic stainless steel was extended to cover the effect(s) of silicon and pre-injected helium gas on dislocation density and swelling characteristics during irradiation in the high voltage electron microscope (HVEM).

Specimens containing 0-1.0 wt% silicon were injected with 10 ppm helium with the use of a variable energy cyclotron. These specimens were irradiated in the HVEM at temperatures in the range 400-650°C. From these experiments the void swelling parameters and dislocation density were determined quantitatively.

In specimens containing silicon up to 0.5 wt% the presence of pre-injected helium leads to higher void density, smaller void size and lower swelling rate at irradiation temperatures up to 600°C; in the case of 1.0 wt% Si, although there is an increase in void density and a decrease in void size, there is no noticeable change in swelling rate up to an irradiation temperature of 600°C.

The pre-injection of helium alters the temperature dependence of void density in two respects: i) the void density becomes less sensitive to irradiation temperature and ii) the high temperature cut-off in void density shifts to higher irradiation temperatures.

The increase in void density at a given temperature due to pre-injected helium is less marked in the steel containing 1.0 wt% Si than in the steel containing no silicon.

The steady-state density of irradiation induced dislocations increases as a result of helium pre-injection, and the relative increase is bigger at higher temperatures.

Effect of vacuum environment on void formation during HVEM irradiation

The vacuum system has been changed in the high voltage electron microscope used for irradiation experiments on void formation. The most important difference is that the partial pressure of water vapour is substantially lower in the new system than in the old system. Irradiation experiments were carried out on cold-worked and annealed pure copper (5N) specimens to evaluate the effect of changes in the vacuum environment.

Specimens of 10, 25, 50 and 70% cold-worked pure copper were irradiated (in the new vacuum) at 250, 350 and 450°C. Void densities determined from these experiments were in good agreement with the results obtained in the old vacuum.

Another series of experiments were carried out in the new vacuum on annealed specimens of the pure copper used in previous experiments. No voids could be formed at 350 and 450°C. Even at 250°C, it was impossible to form voids in many cases. In some cases a few voids were formed at 250°C; but the void density was much lower than in similar experiments done in the old vacuum. In those experiments where voids formed, most of the voids were present in the volume outside the central part of the beam.

Voids were found only in areas containing dislocations, and it was commonly observed that during irradiation no network of dislocations was formed in the central part of the irradiated volume.

These observations can be rationalized in terms of irradiation-induced loss of residual gas atoms. In the presence of grown-in dislocations (like in the case of cold-worked copper), the gas atoms are likely to get trapped at the dislocations. Consequently, the gas atoms are likely to remain in the lattice long enough for nucleation of voids to take place.

Irradiation-induced migration of lattice defects

The process of irradiation-induced dislocation climb under conditions where the point-defect concentrations are governed by interstitial/vacancy recombination was studied theoretically. The recombination process was investigated by computer simulation at the atomic level. The simulation work gave a range of 3.3-6.5 for the recombination cross section in f.c.c. materials, the limits corresponding to spontaneous recombination between nearest neighbours and fourth-nearest neighbours, respectively. The corresponding values obtained by simply counting the number of lattice sites within the range of spontaneous recombination are 12 and 54, respectively. A finite-element technique was used to study arbitrarily shaped (non-symmetrical) diffusion fields around a climbing dislocation. The preliminary results indicate that the climb process is diffusion-controlled and that the climbing dislocation distorts the point-defect population over surprisingly large distances.

Recrystallization of aluminium containing small alumina particles

The presence of small alumina particles in aluminium retards the recrystallization. This phenomenon was investigated by studying the interaction between the alumina particles and the subgrain boundaries in alloys containing low volume fractions of alumina. Subgrain growth was observed to stop after a relatively short anneal at 300°C in an alloy containing 0.08% of alumina. A microstructural investigation of this alloy showed that the particles pinned the subboundaries and inter-

fered with the free movements in the boundary were shown to include the transfer of dislocations from boundary to boundary in the subgrain structure. These transfer processes are essential parts of both subgrain coalescence and low angle boundary migration. Therefore the rate of subgrain growth is reduced if these processes are impeded.

In collaboration with the Danish Academy of Engineering the recrystallization behaviour of an aluminium-alumina alloy cortaining a bimodal distribution of fine alumina particles (<0.1μm) and coarse $FeAl_3$ particles (0.2 - 4 μm) was investigated. The formation and growth of recrystallization nuclei were studied during annealing following 50 and 90% cold rolling, and it was observed that recrystallization nuclei form preferentially at the initial grain boundaries and at deformation bands. The effect of such sites is enhanced by the $FeAl_3$ particles which, however, are not strong nucleation sites themselves. The presence of the $FeAl_3$ particles did not lead to a significant grain refinement and the recrystallized grain size of the aluminium-alumina alloy is large.

Mechanisms of nucleation of recrystallization

Previous work on establishing the nature of the processes involved in the nucleation of recrystallization in dispersion hardened aluminium alloys was extended to include work on other, lower stacking fault energy materials. The purpose of these investigations was to elucidate the limits of applicability in different alloy systems of currently accepted models for the nucleation of recrystallization. The alloy stacking fault energy appears to be of particular importance in this context, both in defining the type of deformation structures developed and in influencing the twinning proclivity during the nucleation processes. An improved understanding of the factors which govern the operation of the various individual nucleation mechanisms is desirable, since important parameters such as the recrystallized grain size depend on the density of nuclei formed during annealing.

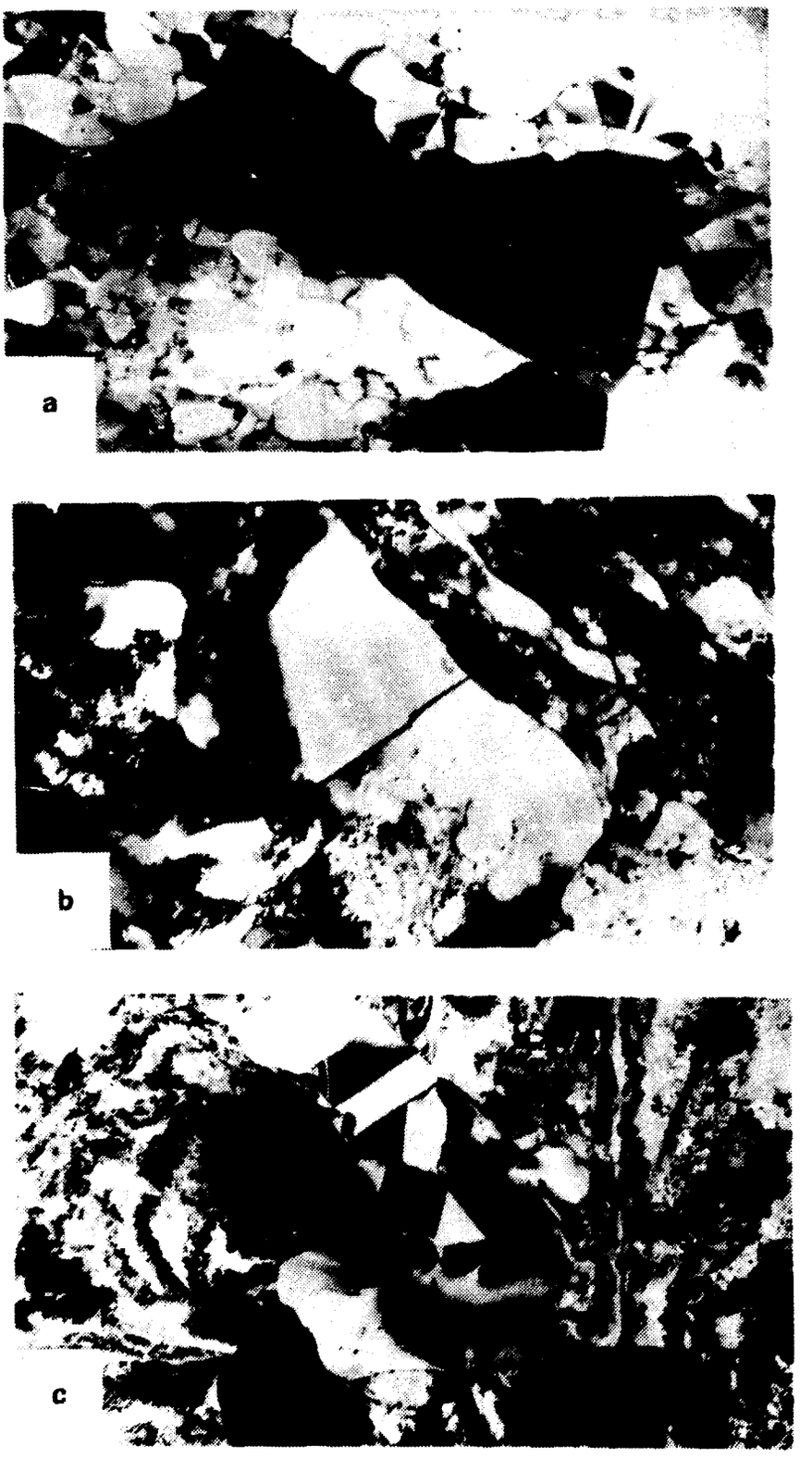

Fig. 3. Nucleation of recrystallized grains at grain boundaries in a) aluminium, b) copper, c) 316 stainless steel. Note the decreasing tendency for cell and subgrain formation and increasing tendency for annealing twinning in nuclei, in going from a) to c).

To study the kinetics of recrystallization the texture of high purity copper was examined by isothermal annealing treatments after 95% cold rolling. The changes in texture during annealing were measured by neutron diffraction which allows continuous in-situ determination of the texture of bulk specimens. As a supplement to the texture measurements the changes in hardness and microstructure were examined after various annealing times.

The reaction of hydrogen with Fe-Ti alloys

Samples of composition FeTi were ball-milled to a grain size of about 100 µm. Hydrogen was absorbed by the samples when they were heated and then cooled to room temperature in a hydrogen atmosphere. When this procedure was repeated 7-10 times the hydrogen absorbed corresponded to a complete formation of the γ-phase ($FeTiH_2$).

Isothermal measurements of the equilibrium hydrogen pressure and corresponding hydrogen content in the solid phase at low pressure (10^{-5}-10^{-1} MPa) showed that Henry's law is not obeyed. At higher pressures the isotherms showed two characteristic pressure levels reflecting the α- and β-phases respectively.

Measurements of the reaction rate at low pressure (10^{-5}-10^{-1} MPa, α-phase) were initiated. At constant pressure the rate showed a local maximum at a hydrogen/metal ratio of about 10^{-3}. This maximum suggests the existence of an adsorbed hydrogen phase as an intermediate in the absorption process.

TECHNOLOGY AND MATERIALS DEVELOPMENT

Materials testing

A servohydraulic universal testing machine (Instron 1333, ± 250 kN) was installed and used for COD tests and normal tensile tests. An equipment for ballooning tests on irradiated tubes was built and installed in the hot cells. Creep tests were carried out to determine residual life time of high temperature components.

Dynamic fracture toughness testing

The crack arrest capability of steel ASTM A533B for nuclear pressure vessel application was examined as part of a multi-national evaluation programme carried out under the auspices of the American Society for Testing and Materials. The minimum value of the dynamic fracture toughness (K_{Im}) and the stress intensity factor at crack arrest (K_{Ia}) were measured with the use of two different test procedures. It was found that the K_{Ia}-values obtained by the two procedures agree very well, whereas the K_{Im}-values determined by one of the procedures were 30% smaller than those determined by the other procedure. The procedures differed much with respect to testing reliability.

Crack opening displacement testing

Crack opening displacement (COD) testing of a high-strength low-alloy structural steel conforming to BS 1501-281A was conducted in order to establish the toughness transition temperature region of 50 mm thick, notched sections (fig. 5). Repeated COD tests revealed a scatter in the fracture mode. At a given temperature in the transition region some specimens failed in the fully ductile mode, while others failed in the brittle mode. This work was a part of a collaborative EEC programme on elasto-

plastic fracture toughness assessment methods, and the results obtained by all partners suggested a degree of scatter of 75°C at a COD level of 1 mm. Figure 6 shows the fracture surfaces from a test conducted at 20°C. The fracture mode is mixed, and the critical COD was 1.07 mm.

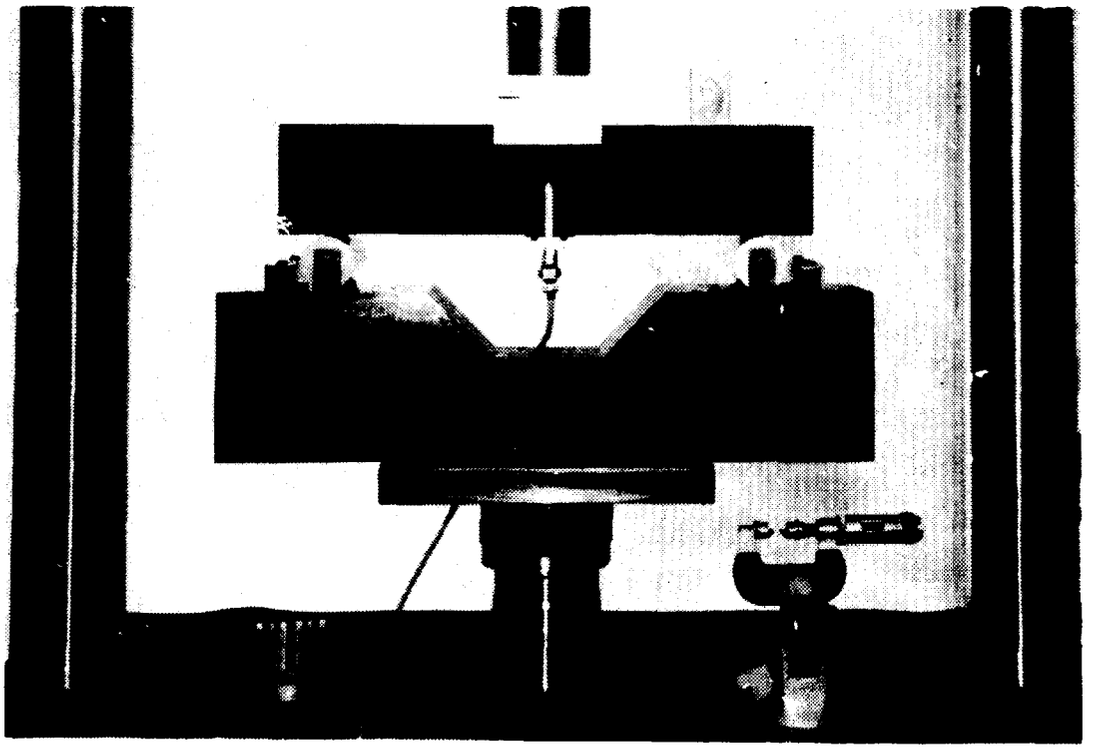

Fig. 5. COD specimen mounted on a bending rig. The specimen is fatigue cracked and COD tested on a servo-controlled INSTRON 1333 testing machine of 250 kW capacity. The specimen dimensions are 500 x 100 x 50 mm^3.

Fig. 6. Fracture surface of a specimen tested at 20°C. The fracture is of a mixed mode with slow ductile crack growth preceding fast brittle fracture (the "pop-in" mode). The specimen was heat treated before the final separation of the fracture surfaces.

Brazing and soldering

The joint project carried out with the Danish Corrosion Centre and the Danish Welding Institute to investigate various cadmium-free silver brazing alloys was completed. The investigation comprised 11 brazing alloys and 9 fluxes from 5 major European manufacturers and silver-tin alloys from 3 European manufacturers.

Investigations of the improvement of wettability by a zirconium getter on nickel-brazed Al- and Ti-alloyed high temperature materials were continued. Further results were ob-

tained in a study of how the strength of the brazed joints varies with different brazing gaps and nickel-based filler metals. The results were compared with results obtained on similar specimens, gaps and filler metals, but with other and more time-consuming pre-treatments of the same pure metal.

The contract work on industrial applications of dip-brazing, vacuum brazing and ultrasonic soldering of aluminium as well as vacuum brazing of stainless steels and nickel alloys was continued.

A new GCA high vacuum furnace "SUPER VII" with an effective hot zone 200 by 200 by 500 mm^3 and controlled by the Honeywell programmer DCP-7700 was installed.

Fibre-reinforced plastics

Development and investigation of fibre reinforced plastics were continued with emphasis on the following areas: Fabrication, characterization, machining, testing, modelling and non-destructive testing. A small autoclave for fabrication of laminates from pre-preg (preimpregnated fibres) was designed and built. It is primarily used for fabrication of laminates of carbon fibre reinforced epoxy. The construction of the mechanical parts for a filament winding machine was completed and the design and fabrication of the electronic operation controller are in progress. Methods were established for determining the fibre content, the density and the void content of glass fibre reinforced polyester.

Tensile tests on small specimens of unidirectional glass fibre/polyester and carbon fibre/epoxy were performed. A larger specimen design (15 x 25 mm cross section, 200 mm gauge length) for tensile test of a glass fibre/polyester laminate was developed. Besides, a study of the fatigue behaviour of carbon fibre/epoxy laminates with and without holes was initiated.

The department acts as a consultant to the Electricity Generating Companies in connection with the building of two wind turbines. The six rotor blades for the 630 kW wind turbines were fabricated in collaboration with Vølund A/S, Viborg and OL-Boats, Ringsted. The work is described in detail in this report under the title "Wingblades of glass-fibre reinforced polyester for a 630 kW wind turbine".

Machining of carbon-fibre reinforced plastics

Cutting of carbon fibre reinforced plastics with single edge tools normally produces surfaces of bad quality. The cutting process was investigated in order to obtain a better quality of the cut surfaces.

The chips were examined by scanning electron microscopy (SEM) and conventional microscopy. This showed that the chips form by a series of brittle fractures.

Investigation of the specimens after the machining showed that cutting parallel to the fibres produces surfaces with good quality: there are no cracks and the roughness is low. Cutting perpendicular to the fibres produces surfaces with high roughness and many cracks, which go obliquely into the specimens. Bad surface quality is partly caused by such cracks.

Metal-hydrogen systems

Pure magnesium reacts with hydrogen at temperatures above 250^{o}C and below 400^{o}C and at hydrogen pressures below 3.5 MPa to form stoichiometric magnesium hydride, MgH_2, in less than 10 minutes. The reaction is independent of the impurity level as found in normal commercial quality magnesium ($\leq$ 5000 ppm) but it depends strongly upon the specific surface area. It was found that a particle size less than 50 µm was satisfactory whereas sizes above 150 µm would slow down the reaction to an extent where stoichiometric composition was not reached within 4 hours.

The magnesium powder will release hydrogen again at 500°C and at pressures below 0.8 MPa. The desorption rate is considerably lower than the sorption rate and is pressure dependent. The desorption effect is of the order of 1.5 kW - 3.5 kW/kg MgH_2 in terms of hydrogen combustion energy.

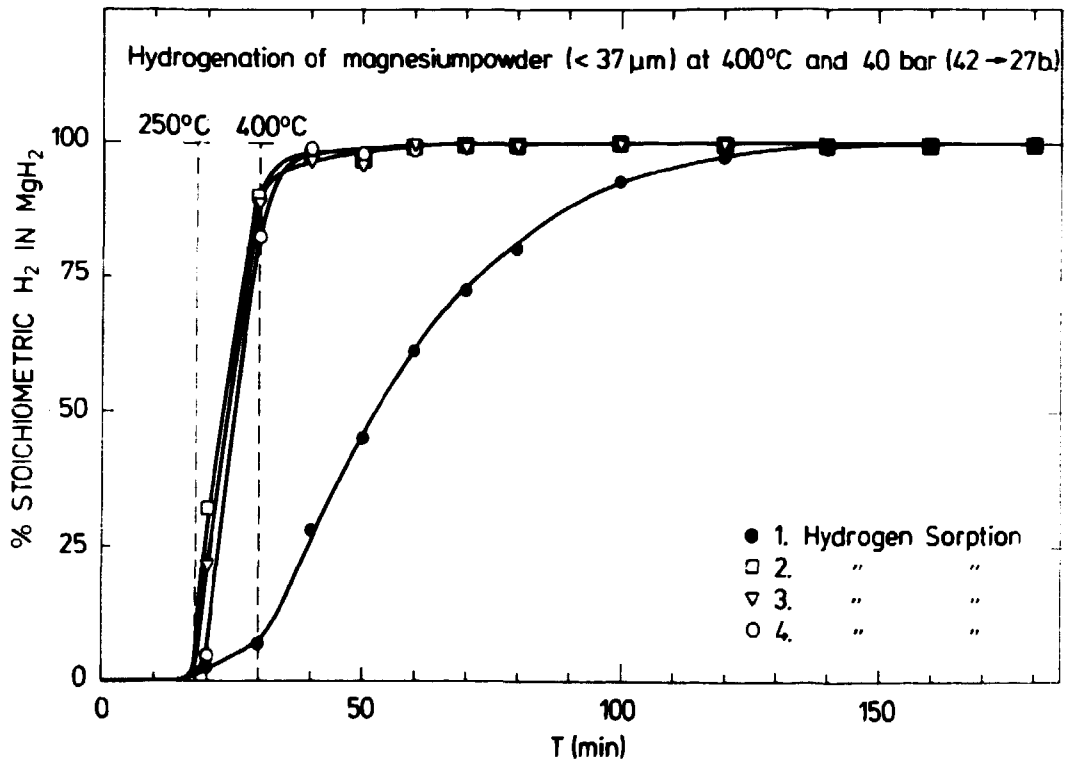

Fig. 4. Cycles of hydrogen sorption-desorption in magnesium powder with complete desorption between each cycle. The sorption rate is lower in the first cycle than in subsequent cycles where the powder is completely hydrided in less than 10 minutes as the temperature is raised from 250°C to 400°C under a maximum hydrogen pressure of 3.5 MPa.

Cycling up to 10 times neither reduces the maximum concentration of hydrogen, nor the sorption/desorption rates. On the contrary, the first cycle is somewhat slower than the following.

Exposure to air (oxygen) is not critical for an already oxidized magnesium powder. After 2 months in air a powder required activation by a new first cycle but behaved otherwise as before exposure.

Exposure of hydrided magnesium, MgH_2, to moist air - even at humidities as low as 35% relative - seemed critical: the hydride slowly reacts to form magnesium oxide which causes a permanent loss of material.

Very little disintegration takes place despite the large expansion (25% vol.) and the ensuing heavy cracking of the powder particles. Since 400°C is a relatively high temperature compared with the melting temperature (651°C), we assume that diffusion bonding in the reducing atmosphere is sufficient to keep the individual particles intact.

Solid electrolytes for lithium batteries

Solid electrolytes based on mixtures of various lithium salts and additives are under examination for future use in "all solid state high energy lithium batteries". Their ac- and dc-conductivity were determined as functions of temperature and composition. The maximum conductivity for Li-ion conduction in the investigated materials is $\sim 0.1 \Omega^{-1} m^{-1}$ at 100°C for solid LiI, H_2O. Small batteries based on the all solid state concept are being tested.

Oxygen conducting solid electrolytes

The optimum conditions for fabrication of CeO_2/Gd_2O_3 electrolytes with high density and homogenous distribution of Gd were established. These conditions are:

a) ball milling of CeO_2 and Gd_2O_3 power mixtures for 50 h.
b) pressing cylindrical specimens in a hydraulic press at a pressure of 3 Pa.
c) sintering in air at 1500°C with a heating rate of 2°C/min below 1000°C and 0.5°C/min in the range of 1000-1500°C.

The density obtained by this process was 96% TD for specimens containing 8,25 and 35 w/o Gd.

Samples of $LaAlO_3$, $NdAlO_3$ $DyAlO_3$ and $GdAlO_3$ doped with CaO were examined by transmission electron microscopy in order to characterize them with respect to presence of porosities and second phase particles. $NdAlO_3$ and $GdAlO_3$ were found to contain isolated second phase particles with a structure analogous to that of β-alumina (R_2O_3, x Al_2O_3, where R = Nd or Gd and x = 11).

Neutron scattering studies of solid electrolytes

Neutron diffraction experiments on plycrystalline $LiI \cdot D_2O$ were carried out to study the crystallographic orientation of D_2O and positions of Li as a function of temperature. The D_2O-molecules, centered in the simple cube of the I-lattice, are preferentially oriented with deuterium along two of the eight equivalent <110> directions; Li-ions are distributed over the sphere containing the six face-centered positions. The anomalous increase in conductivity which was observed between 70°C and 80°C is not reflected in the distribution of Li-ions.

Quasi-elastic neutron scattering experiments were performed on $LiI \cdot H_2O$ in an attempt to study the rotational diffusion of hydrogen. The characteristic diffusion times, however, are too long ($>>10^{-10}$ sec) to be observed.

A predicted stable $LiI \cdot \frac{1}{2}D_2O$ phase above 130°C was searched for by measuring the neutron diffraction pattern of a mixture of LiI, $LiI \cdot D_2O$ as a function of temperature. Only the lines of the simple constituents were observed before melting and the prediction could therefore not be confirmed.

Neutron diffraction experiments were used to support the result from X-ray diffraction experiments that a cubic phase of the electrolyte $LiNaSO_4$ exists in the range of 515°C < T < 6?0°C. The diffraction pattern from a polycrystalline sample of the mixture Li_2SO_4, Na_2SO_4 was rather complex at T = 435°C but contained at 575°C only the lines corresponding to cubic $LiNaSO_4$.

High-level waste disposal

As part of the advisory assistance from Risø to ELSAM/ELKRAFT's waste management project a report on the corrosion aspects of high-level waste disposal in salt domes was prepared. The corrosion behaviour in salt domes of important groups of candidate materials for corrosion protection and shielding of the waste cylinders was reviewed, and the most promising materials or combinations of materials were discussed.

Erosion-corrosion of carbon steel

A study of the corrosion of carbon steel in bicarbonate solutions containing fluoride and chloride at temperatures up to 300°C was initiated with a view to the selection of materials for the uranium pilot plant. A special apparatus for investigation of erosion-corrosion under those conditions was designed and is being built.

FUEL ELEMENTS

The Danish fuel elements in the Kahl and Halden reactors continue to perform well and to demonstrate the adequacy of the design and manufacturing processes.

The irradiation of UO_2-Zr fuel pins in the DR 3 reactor at Risø includes standard BWR and PWR type tests irradiated to very high burn-ups. Special tests such as power ramp tests are also being made.

Additional information on fuel performance becomes available as a result of international collaboration arrangements, i.e., the OECD Halden Reactor Project (Norway), the "Intertramp" (BWR fuel) and the "Overramp" (PWR fuel) projects at Studsvik (Sweden), the information exchange with the NRC (USA), and the EEC sponsored activities (Brussels) relating to Pu recycling in LWRs.

Danish fuel element irradiations in the Kahl and Halden reactors

The four Danish fuel elements in the German BWR power reactor went on power for the first time in 1975. Irradiation was continued and these elements have now achieved an estimated average burn-up of 14,200 MDW/t UO_2. Two short tests fuel pins, manufactured from the same UO_2 and Zr materials as the Kahl fuel pins, have now reached a burn-up of 34,500 MWD/t UO_2 in the DR 3 reactor.

Irradiation of the five test fuel elements in the Halden reactor (Norway) was continued. They have now reached the following estimated burn-ups (average assembly, after correction for fuel depletion):

IFA no.	148	161	165	201	202
MWD/t UO_2	32,500	34,200	32,000	28,000	25,000

The maximum local burn-up of 41,000 MWD/t UO_2 was achieved with IFA 161.

IFA 148 was unloaded at the indicated burn-up and transported to Risø. After dismantling, the fuel pins from this fuel element will be used in an internationally sponsored project at Risø to obtain fission gas release data at very high burn-up. Prior to puncturing and gas extraction, some of the fuel pins will be subjected to a short irradiation in the DR 3 reactor at Risø at power levels above those of the latest part of the irradiation in Halden, but still within usual technical specifications.

UO_2-Zr irradiations at Risø

In the test fuel irradiation programme at the DR 3 reactor, standard fuel pins have reached maximum burn-up levels of 54,200 and 46,500 MWD/t UO_2 for BWR and PWR fuel, respectively. Two ramp tests were performed with BWR test fuel pins at 11,000 MWD/t UO_2.

An evaluation of fission gas release data from Danish ramp tests gave interesting results regarding the effect of hold time at overpower.

Seven PWR and BWR type test fuel pins were irradiated to burn-ups in the range of 11,000-27,000 MWD/t UO_2 at power levels generally decreasing to around 300 W/cm. In subsequent ramp testing, overpower levels in the range of 420-560 W/cm were used, with hold times at overpower of 3 minutes, 17 minutes or 3-4 weeks.

The fission gas releases in these pins fall in three groups:

(a) The week-long hold times at 420-450 W/cm in the lower end of the overpower range resulted in high fission gas releases: 29-42%.

(b) The higher overpower level around 500 W/cm gave a release roughly half as high: 12-18%, during the much shorter hold time of 17 minutes.

(c) The one pin with the highest overpower of 560 W/cm also had the shortest hold time of 3 minutes, and it showed the smallest fission gas release: 3%.

It is thus seen that fairly moderate power increases after a certain burn-up can result in a very significant fission gas release provided the hold time is long enough (group(a)). If hold time was not important for fission gas release, then a higher release rate would be expected for groups (b) and (c). The experiments gave the opposite result; it is thus inferred that the hold times of groups (b) and (c) (17 and 3 minutes, respectively) were not long enough to permit "full" gas release at the given overpower levels.

Computer modelling of fuel pin performance

The detailed deterministic fuel performance code WAFER-3 was coupled with two other codes: the fast, simplistic (and deterministic) code FFRS and the probabilistic code FRP. The resulting code complex is used for comprehensive fuel performance analysis at various levels of detail.

The codes are being used in an evaluation of the special low-interaction UO_2 pellet design LOWI (see previous annual reports). A commercial PWR 17 x 17 design is used as reference. In this study, the gain from using LOWI in terms of relaxed operating restrictions (and thus increased plant availability) is balanced against the somewhat higher manufacturing cost of LOWI fuel.

NON-DESTRUCTIVE TESTING

The projects in this field deal with the development and application of non-destructive techniques for various testing purposes.

Neutron radiography

Comparative neutron radiography of calibrated nuclear fuel pins was continued and neutron radiographs on X-ray and nitrocellulose film were taken in Denmark, France, Canada and U.S.A. They will be evaluated at Risø. Standardization work in the field of neutron radiography was initiated within Euratom, where a Neutron Radiography Working Group was formed under Danish chairmanship. Different tasks within that field were apportioned among the participating countries. The Danish contribution to the Euratom program is an atlas, containing typical defects revealed by neutron radiography in light water reactor fuel. The defects are classified according to their location, nature and origin and are shown in original size on film and as enlarged pictures on paper.

Ultrasonic inspection

A computerized system for three-dimensional rotational scanning of sound waves from ultrasonic transducers was built. The main purpose of the system is to obtain and accurate and detailed enlarged picture of the sound field from high frequency focused transducers. The usual technique in the field around the transducer. The scanning system is showed schematically in fig. 7(a) and the recorded picture of a sound field can be seen in fig. 7(b).

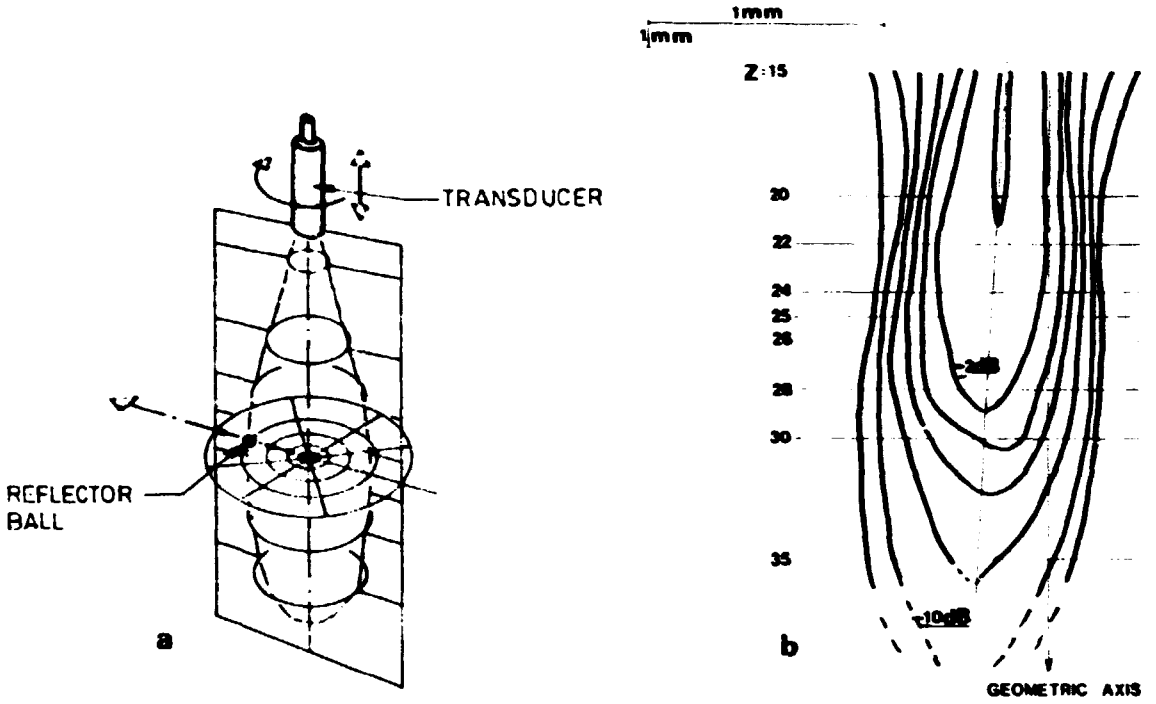

Fig. 7. (a) System for three-dimensiona rotational scanning of sound waves from ultrasonic transducers (schematic). (b) Longitudinal section of a sound field rec ded by the scanning system.

A computerized hydraulic system for two- (or three-) dimensional X-Y scanning of larger areas (or volumes) is being built. The system is intended for ultrasonic inspection of larger components under immersion conditions or for densitometric scanning of X-ray radiographs.

Attempts were made to measure materials properties non-destructively by ultrasound. The materials were characterized in terms of sound velocity and damping.

Acoustic emission assessment system

The experience gained from earlier experimental research in the application of acoustic emission in steel structures was used in the design of a registration and assessment system. The signals generated at a given amplitude are counted and used for making a print-out of the amplitude distribution in steps of 2 dB. Data stored by this method can be transferred and further analysed at the central computer installation.

WINGBLADES OF GLASS FIBRE REINFORCED POLYESTER FOR A 630 kW WINDTURBINE

B.S. Johansen, H. Lilholt and Aa. Lystrup

A windturbine of nominal power 630 kW has been designed and built by the Danish electricity utilities. The department acted as a consultant on materials selection and fabrication. The design of the rotor and of the wingblades was carried out with little previous experience in this field. The main characteristics of the windturbine are as follows:

Nominal power	630 kW
Height of hub	45 m
Rotor, 3 wingblades, upwind of tower	
Rotor diameter	40 m
Wingblade, tip speed	70 m/s
Angular velocity, ω	3.5 s^{-1}
Windspeed, start/max. power/stop	6/13/25 m/s

Design of the wingblades

The three wingblades are composed of an inner wing of length 8 m, and an outer wing of length 12 m. The conceptual design of the wingblade is a (load-bearing) tubular spar with aerodynamically shaped shells. The inner wing has a spar of steel while the outer wing has a D-shaped spar of glassfibre reinforced polyester; the shells are made of polyester with glassmats in a sandwich construction with a balsa core. The use of steel for the inner spar and glass-polyester for the outer spar is a trade-off between the requirement of low weight at large radius and available fabrication methods and dimensions for the glass-polyester spar. A preliminary design was used to evaluate static and dynamic stresses, deflections, and resonance frequencies of the wingblade, in particular the outer

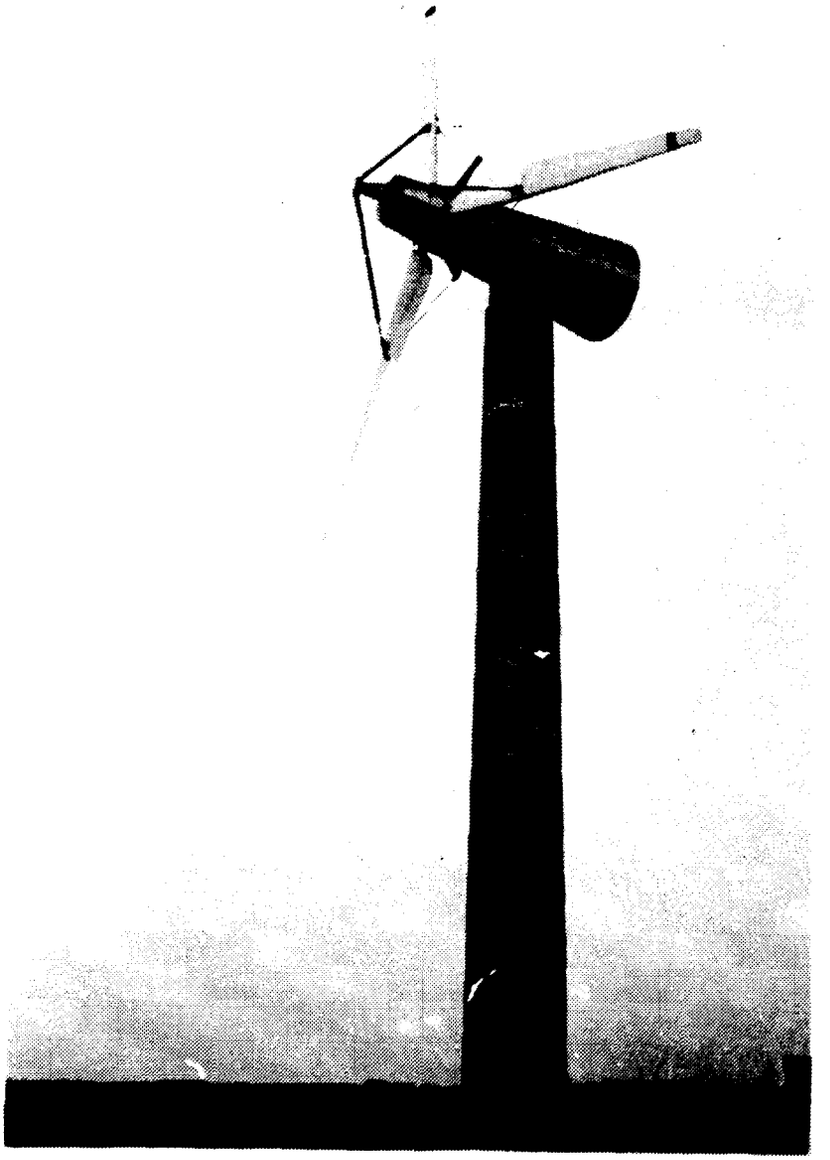

Fig. 8. The 630 kW windturbine on site.

wing. This paper discusses only the design and materials of the outer wing, fig. 9.

The stresses in the outer wing originate from the aerodynamic loads, the centrifugal forces on the rotor and the forces caused by the fact that the wingblades are "tilted backwards" 6^{o} from the rotor plane (the "cone angle force"). The important stresses are the flapwise bending stresses of the wing.

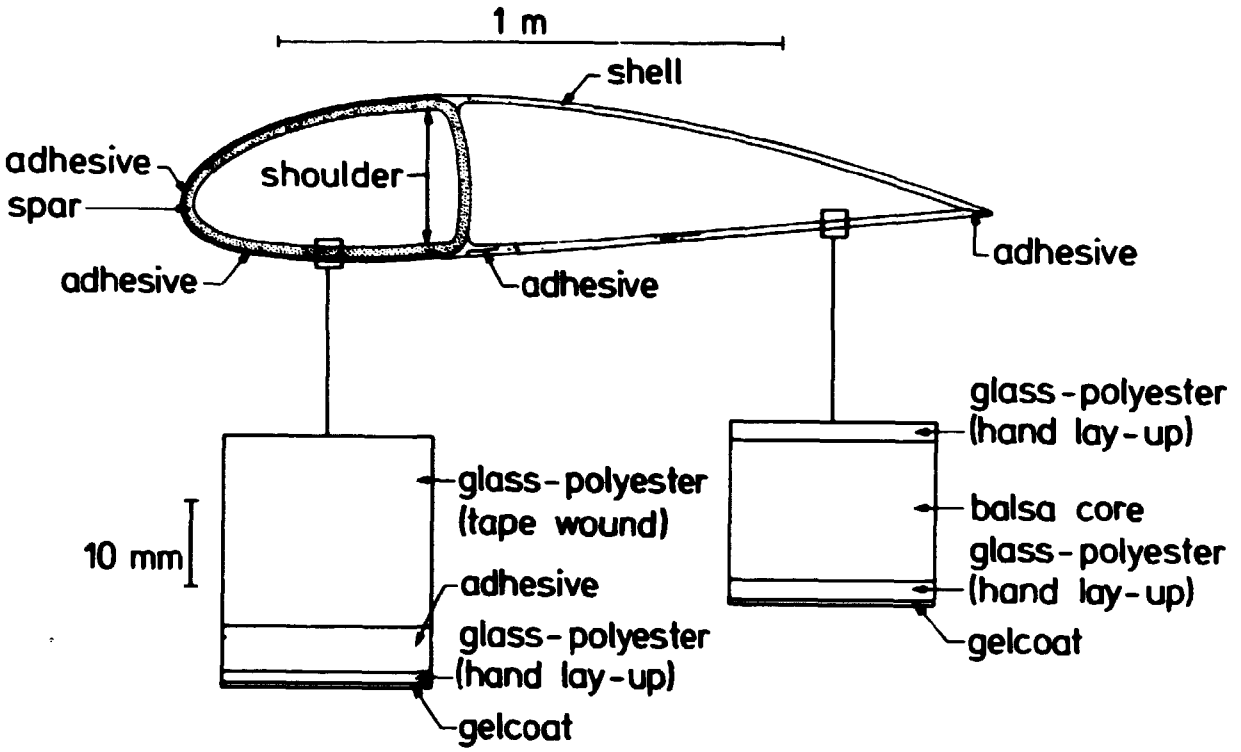

Fig. 9. The cross-section of the outer wing with materials specifications.

The deflection, in the flapwise mode, of the wingtip is approximately 1 m under extreme wind conditions.

The resonance frequency for a single outer wing (12 m length) during rotation is approximately 2.2 Hz; it is assumed that the outer wing is fixed at the strut support at radius 8 m. The three wingblades of the rotor will interact, and the important (lowest) resonance frequency of the rotor is 1.93 Hz. The imposed frequency due to rotation is three times the rotational frequency, i.e., 3 x 0.557 = 1.67 Hz; the margin is thus approximately 15%.

The materials for the spar and shells of the outer wing were based on these performance data.

Materials

The performance requirement lead to a spar material of high (bending) modulus, high static and dynamic strength and of low weight; the torsion modulus is not considered to be a critical material property. Glass fibre reinforced polyester was chosen, rather than e.g. carbon fibre reinforced epoxy, because it is a known material to the (Danish) manufacturing industry. The requirements to the materials properties and the geometrical parameters of the spar suggest a glass-polyester material of high volume fraction (>40 vol%) of glass fibres, and of highly oriented fibres, ideally parallel to the longitudinal axis of the spar.

An available and convenient technique for spar fabrication is (filament) winding of glass fibres onto a mandrel. Traditional filament winding with rovings allows fibre orientations of 20^{o} - 30^{o} at best, which is not acceptable in relation to the required stiffness (elastic modulus).

A winding technique with the use of a wowen glass tape was developed. The glass tape has about 90% of the glass fibres (rovings) transverse to the length of the tape, with the remaining 10% of glass forming lengthwise supporting rovings. Winding of this tape onto a mandrel produces a laminate with the 90% fibres nearly parallel to the axis of the spar and the 10% fibres nearly at 90^{o} to the axis.

The wall thickness of the spar was determined from the design calculation programme, based on the finite element method, and ranges from 24 mm at the root to 6 mm at the tip of the spar (referred to the "shoulder" position). The resulting flexural rigidity of the wing falls off, from root to tip, faster than linearly.

The requirements to the shell material are low weight, high bending stiffness and reasonable strength. These requirements are met by a sandwich material of polyester with glass mats and a balsa core. This material is well known to the industry,

in particular the boat builders. The specifications comprise gelcoat (external surface), 1-2 mm glass-polyester, 10-16 mm balsa, and 1-2 mm glass-polyester (internal surface). Those parts of the shell, which enclose the spar, have no balsa core.

Fabrication

The spars were fabricated on a (conventional) filament winding machine, which was modified for the tape winding technique. The mandrel, of shape equal to the internal shape of the spar, was made of a supporting steel tube, fitted with a skin of steel plates, that gives the outer D-shape. The mandrel was supported at its ends and driven by the machinery through the root end support bearing.

During tape winding the machine (fig. 10) was operated with a constant advancement of the tape feed arrangement along the mandrel; thus a constant ratio was maintained between the rotational speed of the mandrel and the linear movement of the tape feed arrangement, but the speed of winding could be varied. The glass tape, of weight 256 g/m^2, was 0.21 m wide and

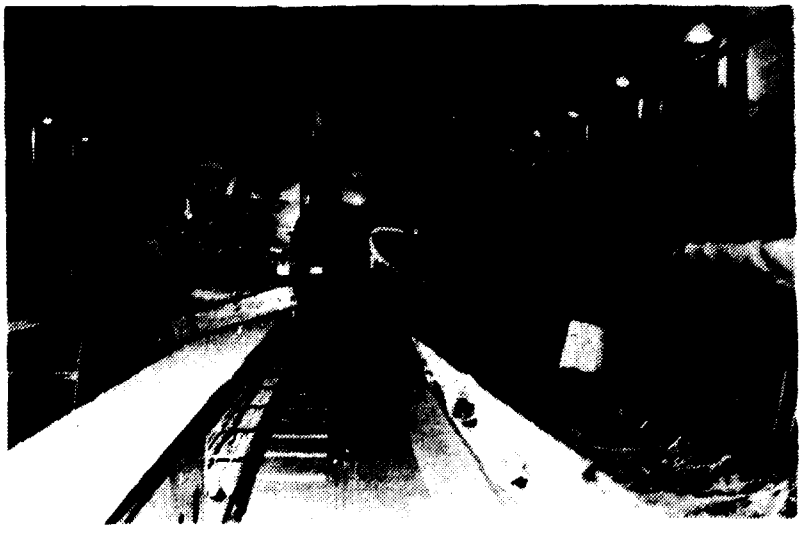

Fig. 10. Tape winding of spar; the mandrel with some layers of glass tape is to the right, and the tape feed arrangement with roll of glass tape and soaking apparatus is to the left.

was wound with nearly half overlap such that the effective width of the tape during the winding was B ≈ 0.10 m. Winding with half overlap causes a double layer of tape to be laid down during each travel along the mandrel.

Two important differences occur relative to (tape) winding onto a straight cylindrical mandrel:

1) The conical shape, which determines the fibre orientation θ, also governs the direction from which the tape must approach the mandrel. A mechanical arrangement was built to control the varying angle of the tape feed during the linear movement along the mandrel.

2) The conical shape and the finite width of the tape have the effect that one side of the tape will always be tight around the mandrel while the other side of the tape will always be slack. It is necessary to take up this slack continuously in order to maintain the correct placing of the tape and the correct angle of fibre orientation. The take-up of the slack is done by inserting a wedge under the tape and withdrawing it after the next revolution. The correct feed of the tape onto the mandrel is controlled visually by the person who operates the wedge (fig. 11).

Fig. 11. The wedge is inserted during tape winding.

The glass tape is supplied with polyester by passing through a soaking apparatus mounted on the tape feed arrangement. The amount of polyester carried by the tape governs the volume fraction of glass in the laminate, and the soaking apparatus needs careful adjustment to ensure high volume fractions (>40%).

The shells for the wing are fabricated in the traditional way by hand lay-up in moulds, made from a complete model of the wing.

The assembling of the wing is made by adhesive bonding of the spar into the shells; the operation is done in two steps, the first step allows an inspection of the position of the spar inside the shells. The completed outer wing (including steel parts for the connection to the inner wing) weighs 910 kg.

Fabrication control

The tape winding process was monitored in detail; the amount of glass fibres and the amount of polyester was recorded continuously, and this confirmed a uniform supply of raw materials to the mandrel, ensuring constant material composition throughout the spar (with the previously mentioned variations along the circumference). The viscosity of the polyester was measured regularly during fabrication and adjusted, if necessary, to a (not known) constant value by varying the styrene content of the polyester. A constant viscosity of the polyester proved beneficial in controlling the soaking of the glass tape, and thus ensuring a constant volume fraction of glass.

The fibre orientations were measured at regular intervals during fabrication and were within $\pm 10^{o}$ of the axis of the spar, most of them probably within $\pm 5^{o}$, referring to the "longitudinal" fibres.

The thickness of the laminate was measured at regular intervals during fabrication, and the final thicknesses were in agreement with the nominal thickness.

Conclusions

The fabricated spars and wings show the expected mechanical behaviour, and the materials and the design have met the requirements. In particular, it was possible to "design" the glass-polyester laminate for the spar such that the material properties are acceptable. It is not likely that the mechanical properties, e.g. the tensile modulus, can be increased further for the present materials combination (glass and polyester) and fabrication method (tape winding).

PARTICIPATION IN INTERNATIONAL COLLABORATION

The department is engaged in the following types of international collaboration: joint technical projects, committee work, reception of research fellows, and technical and scientific meetings. A formal agreement has been reached with the USSR State Committee for the Utilization of Atomic Energy concerning a technical cooperation programme on irradiation damage between the department and the Kharkov Physical-Technical Institute.

The department was represented on the following committees:

The Information Exchange Group under the European Space Agency on Carbon Fibre Reinforced Plastics,

The Halden Programme Group,

The IAEA International Working Groups on "Reliability of Reactor Pressure Components" and "Water Reactor Fuel Performance and Technology",

The "Interramp" and the "Overramp" Project Committees,

The OECD/EEC Nuclear Agency's Committee on the Safety of Nuclear Installations (NEA-CSNI) Working Group on Safety Aspects of Steel Components in Nuclear Installations,

The Working Group "Nuclear Corrosion" under the "European Federation of Corrosion",

The COST 501 Committee on Materials for Energy Conversion using Fossile Fuels.

The EEC Advisory Committees for Programme Management: "Plutonium and Transuranium Elements", "High Temperature Materials" and "Plutonium Recycling in Thermal Reactors",

The Council of the International Confederation of Thermal Analysis,

The Nordic Committee for Thermal Analysis,

and in the Technical Commission of the International Institute of Welding, Commission I, "Gas Welding and Allied Processes", Subcommission A, "Brazing and Surfacing".

EDUCATION AND TRAINING

N. Hansen and K. Rørbo gave regular lectures on materials science to students at the Danish Academy of Engineering. C.P. Debel, T. Leffers, H.. Lilholt, O. Bøcker pedersen, K. Rørbo, and B.N. Singh lectured on physical materials science to students at the Tecnical University of Denmark. N. Hansen, T. Leffers and H. Lilholt acted as external examiners at examinations for the Tecnical University of Denmark, and O. Toft Sørensen acted as external examiner at examinations for the Technical University of Norway, Trondheim. J. Bilde-Sørensen, T. Leffers and O. Toft Sørensen lectured in a course in "Modern Methods in Materials Research" arranged by the Danish Society of Engineers.

One scholarship holder from India worked in the Department on projects in the field of post-irradiation examination.

Post-graduate projects

Three post-graduate students from the Technical University of Denmark and one from the University of Copenhagen worked in the Department on the following projects in preparation for their licentiate Ph.D.) theses:

A. Schrøder Pedersen:	Kinetics of the hydrogen uptake in and release from Fe-Ti alloys,
A. Koplev:	Machining of fibre-reinforced plastics,
K.V. Rasmussen:	Fatigue phenomena in copper,
J. Vestergaard:	Thermomechanical forming processes.

PARTICIPATION IN THE HI-79 EXHIBITION

Risø participated in the Industrial Exhibition which took place in Herning from 4-8 September 1979. The Metallurgy Department contributed posters, slides and working equipment to the stand.

PUBLICATIONS

Metallurgy Department Progress Report for the period 1 January to 31 December 1978.
Risø-R-402 (1979) 59 pp.

The activities of the Metallurgy Department at Risø during 1978 are described. The work is presented in four chapters: General Materials Research, Technology and Materials Development, Fuel Element, and Non-Destructive Testing. Furthermore, a survey is given of the department's participation in international collaboration and of its activities within education and training. A list (with abstracts) of publications and lectures by the staff during 1978 is included.

Radioactive Ion Implantation as a Tool for Wear Measurements.
C. Bagger and G. Sørensen, Isotopenpraxis 15 (1979) 44-46.

The present paper deals with ion implantation of radioactive krypton ions in surfaces with aim of measuring wear of different magnetic materials in sound-heads. The technique is especially suited for a relatively fast comparison of wear-characteristics of materials of varying composition in small inaccessible areas. In the present case utilisation of a 60 KeV accelerator allows determination of a total wear as small as 0.05 µm with an accuracy of 10%. Further the technique yields information of the time dependence of the wear process with an accuracy less than 0.001 µm.

Måling af slid ved hjælp af implanterede radioaktive ioner. (Measurement of Wear by the Aid of Implanted Radioactive Ions).
C. Bagger and G. Sørensen, In: Slid, Proceedings of Dansk Metallurgisk Selskabs Vintermøde, Skjoldnæsholm, 3-4 January 1979. Edited by E.W. Langer and T.S. Nielsen (Dansk Metallurgisk Selskab, Lyngby, 1979) 91-102.

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TEM Method for Identification of Domains in Materials Which Undergo a Pm3m → R3c or R$\bar{3}$c Phase Transition.

J.B. Bilde-Sørensen, phys. stat. sol. (a) 55 (1979) 747-750.

The c-axis of the domains formed by a Pm3m → R3c or R$\bar{3}$c phase transition may lie along any of the four $\langle 111 \rangle_C$ directions of the cubic phase. It is shown that the orientation of the c-axis can be determined by TEM by examining whether two suitable $\frac{1}{2}\{113\}_C$ superlattice reflections are allowed or forbidden in the trigonal phase. As an example, the method is used to examine domains in $LaAlO_3$.

Additive Strength Contributions in Cu-Al_2O_3 Polycrystals.

P. Brøndsted, In: Strength of Metals and Alloys, Proceedings of the 5th International Conference on Strength of Metals and Alloys, Aachen, 27-31 August 1979. Vol. 2. Edited by P. Haasen, V. Gerold and G. Kostorz (Pergamon Press, Oxford, 1979) 1351-1356.

The strength of a dispersion-hardened polycrystal can be expressed as a function of the individual strength contributions which arise from the matrix, the particles, and the grain boundaries. In an attempt to relate these individual strength contributions a series of tensile tests have been carried out at room temperature on a number of different copper specimens containing alumina particles; single and polycrystalline specimens both with and without a particle dispersion have been tested.

The matrix strength contribution has been calculated from shear stress-strain curves of pure copper single crystals.

The particle strength contributions have also been deduced from shear stress-strain curves of Cu-Al_2O_3 single crystals, by assuming that the matrix strength and the particle strength contributions are linearly additive.

Structural parameters such as the sizes, spacings, and volume fractions of the particles have been determined. Using these parameters, a strength-structure relationship is discussed on the basis of Ashby's theory for dispersion hardening.

The strength contribution from grain boundaries has been obtained from stress-strain curves of copper polycrystals of different grain sizes. It was found that the relationship between the flow stress and the grain size could be described by the Hall-Petch equation.

It has been found that the 0.2% flow stress can be calculated by a linear addition of the individual contributions, whereas for flow stresses at higher strains a simple addition cannot describe the observed behavior.

Xenon, Krypton and Helium Release in High Burn-Up UO_2-Zr Fuel Rods.

H. Carlsen, In: Report EUR 6600 EN, Workshop on Fission Gas Behaviour in Nuclear Fuels, Karlsruhe 26-27 October 1978. Edited by C. Ronchi, Hj. Matzke, J. v. d. Laar and H. Blank (European Institute for Transuranium Elements, Karlsruhe, 1979) 139-149.

The abstract appeared in the previous progress report p. 51.

Flammelodning ved montage. (Aspects of Occupational Hygiene During Manual Flame Brazing).

E. Beck Hansen, O. Borring Sørensen and J. Christensen, Svejsecentralen Report No. 79.24 (1979) 89 pp.

As a revision of the Danish legislation on occupational hygiene has imposed very strict limitations on the use of cadmium-containing silver brazing metals, a joint project has been carried out to investigate various commercially available cadmium-free silver brazing metals for use on steels and copper.

In this project, the wettability and the mechanical properties have been investigated by this department, the corrosion from fluxes and flux residues by the Danish Corrosion Centre, and the fumes developed during flame brazing by the Danish Welding Institute.

Experimental Evaluation of Brittle Crack Propagation Velocity - an Improved Technique.

C.P. Debel, Eng. Fracture Mech. 11 (1979) 423-430.

A short review of experimental methods currently used in evaluating the velocity of fast crack extension is given. The technique of applying a surface deposited grid gauge has been innovated. This new technique involves a grid produced by a photo-chemical method and an electronic registration circuit based on integrated transistor-transistor logic. This new method has been applied to experimental studies of brittle crack extension in steel at temperatures between -115 and +22°C.

Dynamic Fracture Toughness Testing of Structural Steels.
C.P. Debel, In: CSNI Report 32, Proceedings of the Specialists Meeting on Elastoplastic Fracture Mechanics, Daresbury, 22-24 May 1978. Vol. 1 (UKAEA, Risley, 1978) Paper 9, 37 pp.

The abstract appeared in the previous progress report p. 52.

Comparison of Image Quality of Nuclear Fuel Neutron Radiographs taken on Silver Halide and Nitrocellulose Film.
J.C. Domanus, Risø-M-2170 (1979) 6 pp.

For the assessment of image quality of nuclear fuel by neutron radiographs the ASTM method seems inadequate; therefore another method was tested, used previously for the assessment of the accuracy of dimension measurements. Silver halide and nitrocellulose films were used in the comparison.

First Attempt to Classify Defects Revealed by Neutron Radiography in Nuclear Fuel for Light Water Reactors.
J.C. Domanus, Risø-M-2171 (1979) 7 pp.

From about 2000 neutron radiographs taken routinely mainly during post irradiation examination of reactor fuel, typical defects were chosen to establish a classification of defects. They are also classified according to their intensity. The classification is illustrated with characteristic defects for each location where they may occur.

Dansk initiativ til ikke-destruktiv prøvning af reaktorbrændsel. (Danish Initiative Concerning Non-Destructive Testing of Reactor Fuel).
J. Domanus, ingeniøren 5 No. 28 (1979) 17.

During routine control of fuel elements in the post-irradiation examination neutron radiography is used. As such examinations are often performed on an international basis, it was felt that standard methods and procedures shall be developed. Initiative was taken to establish a special Euratom working group on that subject. During the first meeting of the group program of work was established and different tasks distributed among the participating countries.

Papir-radiografi er billigere og hurtigere end film. Kan erstatte filmradiografi på en lang række områder. (Paper Radiography is Cheaper and Faster than Film Radiography. It may Replace Film Radiography in many Cases).

J. Domanus, ingeniøren 5 No. 30 (1979) 4.

Radiography on film and paper is compared and many advantages of paper radiography shown: lower cost, higher speed of control and processing, simpler X-ray machines, easier radiation protection problems and simpler radiographic facilities. Examples are given of use of paper radiography (in nuclear industry, pipeline control, aeronautics).

Neutron Radiographic Findings in Light Water Reactor Fuel.

J.C. Domanus, Report (1979) 92 pp.

Typical defects found during neutron radiography of light water reactor fuel are collected and presented as neutron radiographs on film as well as enlargements (2 X) on paper. Those defects were classified according to their location and nature and origin. This atlas is designed as a help for the assessment of neutron radiograph of nuclear fuel and will be enlarged in the future.

Three Dimensional Sound Field Examination. A Computer Aided Scanning System.

H.E. Gundtoft and T. Nielsen, Risø-M-2181 (1979) 8 pp.

By a combination of rotating an ultrasonic transducer and moving a ball reflector a three-dimensional scanning pattern of the sound field is made. A computer controls the scanning and stores the results for further evaluation.

The Effect of Grain Size and Strain on the Tensile Flow Stress of Copper at Room Temperature.

N. Hansen, In: Strength of Metals and Alloys, Proceedings of the 5th International Conference on Strength of Metals and Alloys, Aachen, 27-31 August 1979. Vol. 2. Edited by P. Haasen, V. Gerold and G. Kostorz (Pergamon Press, Oxford, 1979) 849-854.

Tensile stress-strain data were obtained at room temperature for 99.999% copper as a function of grain size. The flow stress-grain size relationship can be expressed by a modified Petch-Hall equation in the grain size range 0.012-0.22 mm and in the strain interval 0.03 to 0.30. The slope in this equation is not significantly affected by the strain.

The flow stress-grain size relationship was analyzed at intermediate strains in terms of matrix strengthening and grain boundary strengthening according to the dislocation concept by Ashby. This approach gives a good description of the effect of grain size and strain on the flow stress, indicating that grain boundary strengthening may primarily be due to an increase in the dislocation density caused by the presence of grain boundaries.

Risø vil få adgang til russiske forsøgsanlæg. (Risø will gain Admittance to Russian Research Facilities).

N. Hansen and T. Leffers, ingeniøren 5 No. 32 (1979) 9.

The article describes an agreement between the Metallurgy Department at Risø and the Physical-Technical Institute, Kharkov.

Risøs Metallurgi vidgar Sovjetsamverkan inom kärnenergi. (The Risø Metallurgy Department extends the Sovjet Collaboration within Nuclear Energy).

N. Hansen and T. Leffers, Jernkont. Ann. 163 No. 5 (1979) 36-37.

The article describes an agreement between the Metallurgy Department at Risø and the Physical-Technical Institute, Kharkov.

Initial Stages of Recrystallization in Aluminum of Commercial Purity.

B. Bay and N. Hansen, Metall. Trans. A 10 (1979) 279-288.

In commercial aluminum with a purity of 99.4 pct, the formation and growth of recrystallization nuclei were studied by techniques such as in-situ annealing in a high voltage electron microscope, transmission electron microscopy and light microscopy. Sample parameters were the initial grain size (370 and 19 microns) and the degree of deformation (50 and 90 pct reduction in thickness by cold-rolling). It was found that the initial grain boundaries and high angle boundaries within the original grains are preferential sites for recrystallization nuclei, and that the effect of such sites is enhanced by the $FeAl_3$ particles present in the commercial aluminum as impurities. The nucleation temperatures determined by high voltage electron microscopy and transmission electron microscopy decrease markedly when the initial grain size is decreased both after 50 and 90 pct cold rolling; a less pronounced temperature decrease is obtained by increasing the degree of deformation. The size of the recrystallization nuclei, the recrystallization temperature and the recrystallized grain size are reported for the four sample states, and finally the structural and kinetic observations are discussed.

Industrien skal bruge A-energi. (The Industry needs Nuclear Power).

A. Jensen, Berlingske Tidendes kronik 10 August 1979.

Feature article that deals with the industrial need for sufficient and effective energy supply, and the role of nuclear power for fulfilling such needs.

Reparation af 3 stk. vinger til Risagermøllen. (Repair of Three Rotor Blades for the Risager Wind Turbine).

F. Jensen, J. Kjøller and Aa. Lystrup, Report (1979) 15 pp.

One year in operation had resulted in small cracks in the glass fiber reinforced polyester air-foil of all three rotor blades of a Risager wind turbine. This report evaluates the extent of the damage, prescribes a repair procedure, and describes and illustrates the repair work.

Subgrain Coalescence and the Nucleation of Recrystallization at Grain Boundaries in Aluminium.

A.R. Jones, B. Ralph and N. Hansen, Proc. Roy. Soc. (London) A 368 (1979) 345-357.

An experimental study has been made of recrystallization processes which have been initiated at grain boundaries in aluminium samples. The samples had an initial grain size of between 30 and 130 μm and were deformed 50% by rolling before annealing at 573 K. The microstructures developed in the region of the grain boundaries, after annealing times chosen just to initiate recrystallization, have been investigated with transmission electron microscopy. A major part of the investigation has been the identification of a number of different types of potential recrystallization nuclei at these sites.

It has been established that the formation of most of these recrystallization nuclei involves modifications to the subgrain structures adjacent to grain boundaries. A model is developed for the formation of recrystallization nuclei at grain boundaries by processes involving subgrain coalescence. The microstructures predicted by the model are in accord with those observed experimentally.

Grain to Grain Variations in NbC Particle Size Distributions in an Austenitic Stainless Steel.

C.Y. Barlow, B. Ralph, B. Silverman and A.R. Jones, J. Mater. Sci. 14 (1979) 423-430.

Quantitative information has been obtained concerning the size distributions of NbC precipitate particles in different grains in a deformed and aged austenitic stainless steel specimen. The precipitate size distributions obtained differ from one grain to another. The average disparity measured between the mean precipitate sizes was a function of the distance between the grains compared. The results obtained are considered in terms of differences in precipitation behaviour due to variations in the levels of plastic strain in constituent grains of the deformed specimen.

On the Measurement of the Misorientation across Low-Angle Boundaries.

A.R. Jones, J. Mater. Sci. 14 (1979) 2018-2019.

A simple experimental method of determining the misorientation between subgrains was determined. The accuracy of the method is improved by making use of the Moiré fringe manifestation of one component of boundary misorientation.

Nucleation of Recrystallization in Aluminium containing Dispersions of Alumina.

A.R. Jones, B. Ralph and N. Hansen, Metal Sci. J. 13 (1979) 149-154.

The abstract appeared in the previous progress report p. 53.

Recrystallization of Microduplex Steels.

B.A. Cooke, A.R. Jones and B. Ralph, Metal Sci. J. 13 (1979) 179-186.

The effects of high-temperature annealing on cold-worked microduplex austenite/ferrite stainless steels have been studied by following the hardness variations with time and investigating the resulting microstructural changes using transmission electron microscopy. It has been found that the resulting microstructures are affected by the relative volume fractions of austenite and ferrite present initially, by the deformation level, and by the temperature and time of the anneal. A well-defined subgrain structure was found to form in the ferrite phase during the earliest stages of annealing in all the cases investigated. By contrast, the austenitic phase volumes exhibited only a limited tendency to develop observable recovered dislocation substructures.

Where the austenite was found to recrystallize, the process could be seen to have occurred discontinuously by movement of a high-angle interface. However, the mechanisms for recrystallization of the ferrite depended on phase volume fractions. In specimens which contained approximately equal volume fractions of ferrite and austenite a continuous recrystallization process was found, whereas a discontinuous mechanism was observed in specimens which comprised about 75 vol.-% ferrite.

WAFER-3. An Extended Version for High-Speed Analysis of Rods with an Axial Power Profile.

N. Kjær-Pedersen, In: Transactions of the 5th International Conference on Structural Mechanics in Reactor Technology, Berlin, 13-17 August 1979. Vol. D. Edited by T.A. Jaeger and B.A. Boley (Commission of the European Communities, Luxembourg, 1979). Paper D1/5, 10 pp.

The Danish fuel performance code WAFER is designed for optimal, simplistic analysis of LWR fuel rod performance. The code does a detailed one-dimensional thermo-mechanical analysis of the fuel rod in response to an arbitrary power history. The effect of localized straining of the cladding at pellet/pellet interface positions (ridging) is accounted for through an energy principle.

The previous version, WAFER-2 (presented at SMIRT-4) is a one-axial-node model. WAFER-3 allows many axial nodes and can therefore account for the interplay between the axial power profile, the fission gas release and the axially distributed fuel temperatures, as well as mechanical effects of the axial variations of the axial fuel/clad interaction forces.

Further, considerable gain in computing speed has been achieved through optimization of the coding.

Fiberforstærket plast. (Fibre Reinforced Plastics).

J. Kjøller, Metal No. 10 (1979) 14-15.

The stiffness, strength and weight of composite materials are compared with those of other structural materials. Potential applications of composite materials are discussed.

Evaluation of LWR Fuel Performance Under Transient and Off-Normal Conditions. A Review of Recent Reports.

P. Knudsen, Risø-M-2211 (1979) 80 pp.

Reports from the meetings at Petten (Nov. - Dec. 1978), Portland (April-May 1979) and Arles (May 1979) have been reviewed together with various reports related to the Three-Mile Island accident. The reports were selected to cover transients in normal operation (power ramps, load-following) as well as off-normal transients.

PWR Type Overpower Tests at 1620 GJ/KGU (18.800 MWD/MTU).
P. Knudsen, C. Bagger and H. Carlsen, In: Light Water Reactor Fuel Performance, Proceedings of the ANS Topical Meeting on Light Water Reactor Fuel Performance, Portland, Oregon, 30 April - 2 May 1979. (American Nuclear Society, La Grange Park, Illinois, 1979). 264-273.

Three PWR type test fuel pins accumulated a burnup of 1620 GJ/kgU at heat loads decreasing from 45 to 28 kW/m (avg. test levels). One pin was ramped to 43 kW/m at 31 W/m/s; after 15 ks the power was increased to 45 kW/m and held constant for 1.9 Ms without failure indication. The other two pins were ramped to 44 kW/m at 23 W/m/s and then to 49 kW/m in a further 1.2 ks; both failed after max. 360 s. The post-irradiation examination revealed large stress-corrosion (SCC) type cladding cracks. Other cracks, down to a few μm deep, were probably early stages of large SCC cracks. Fission gas release in the intact pin was as high as 42% and estimated to be much lower for the two failed pins. The observations on fission gas release, fuel structure, and cladding and fuel deformations strongly indicate that the long hold-time for the intact fuel pin permitted the operation of diffusion and creep processes in spite of the lower overpower level.

Bearbejdning af kulfiber-epoxy komposit. (Machining of Carbon-Fibre/Epoxy Composite).
A. Koplev, In: Metallernes Bearbejdning, Proces- og Produktionsteknik. Proceedings of a Symposium held at the Technical University of Denmark, Lyngby, 19-21 March 1979. Edited by M.P. Schreiber (AMT, Danmarks tekniske Højskole, Lyngby, 1979) 45-51.

Problems related to the chip-forming machining of carbon-epoxy components are considered. Experimental evidence for a rapid wear is presented and compared with evidence for steel. It is suggested that the rapid wear is caused by friction heating of the tool.

High-Pressure Liquid Chromatography of Irradiated Nuclear Fuel: Separation of Neodymium for Burn-Up Determination.
N.R. Larsen, J. Radioanal. Chem. 52 (1979) 85-91.

Neodymium is separated from solutions of spent nuclear fuel by high-pressure liquid chromatography in methanol-nitric acid-water media using an anion-exchange column. Chromatograms obtained by monitoring at 280 nm, illustrate the difficulties especially with the fission product ruthenium in nuclear chemistry. Preseparation of the rare earths and trivalent actinides using a di(2-ethylhexyl)phosphoric acid/kieselguhr column is described.

Isotope Analysis. Radiochemical Burn-Up Determination.
N.R. Larsen and E. Larsen, Risø-M-2183 (1979) 32 pp.

The radiochemical analysis of heavy isotopes (uranium, plutonium, americium, and curium isotopes) and burn-up (Nd148 method) in samples of irradiated nuclear fuels is described. The analysis is based on isotope dilution technique in combination with mass spectrometry and alpha spectrometry.

A Modified Sachs Approach to the Plastic Deformation of Polycrystals as a Realistic Alternative to the Taylor Model.
T. Leffers, In: Strength of Metals and Alloys, Proceedings of the 5th International Conference on Strength of Metals and Alloys, Aachen, 27-31 August 1979. Vol. 2. Edited by P. Haasen, V. Gerold and G. Kostorz (Pergamon Press, Oxford, 1979) 769-774.

A modified Sachs model is suggested as an alternative to the Taylor model. The model describes a situation with inhomogeneous multiple slip. Material continuity is fulfilled via the fulfilment of microscopic compatibility by secondary slip.

Loop Growth and Point-Defect Profiles during HVEM Irradiation.
T. Leffers and B.N. Singh, phys. stat. sol. (a) 54 (1979) 621-631.

The point-defect profile in a thin foil is included in the model for the growth of dislocation loops during HVEM irradiation suggested by Kiritani, Yoshida, Takata, and Machara, and the possible effect of divacancies is discussed. It is found that there is a fairly wide transition range between the two extreme cases described by Kiritani et al. (the vacancy- and the surface-dominant case); this can directly (without the necessity of a divacancy effect) explain the observation of apparent activation energies for loop growth smaller than $\frac{1}{2} E_V^M$ (where E_V^M is the vacancy migration energy). Even after the inclusion of the point-defect profiles there are indications that the model cannot fully account for the loop growth behaviour in situations where surface losses and recombination losses are comparable.

The Effect of Cold Work on Void Formation and Growth in Copper during High Voltage Electron Microscope Irradiation.

T. Leffers, B.N. Singh, S.N. Buckley and S.A. Manthorpe, In: Irradiation Behaviour of Metallic Materials for Fast Reactor Core Components, Proceedings of the International Conference on the Irradiation Behaviour of Metallic Materials for Fast Reactor Core Components, Ajaccio, 4-8 June 1979. Edited by J. Poirier and J.M. Dupouy (Le Commisariat a l'Energie Atomique, Gif-sur-Yvette, 1979) 235-240.

Copper is used as a model material for the study of the effect of cold work on void swelling. The irradiations are done in a high voltage electron microscope. Irradiation temperature and degree of cold work are varied in the ranges 250-450°C and 0-90%, respectively.

Brudforhold i fiberforstærkede materialer. (Fracture Behaviour of Fibre-Reinforced Materials).

H. Lilholt, materialnyt No. 2 (1979) 61-71.

The fracture processes in fibre composites are presented. The energy balance and the fracture mechanism of the various processes are described. The size, shape and orientation of cracks are discussed. The possible use of fracture mechanics calculations for fibre composites is discussed.

Mekaniske og fysiske egenskaber af fiberkompositter. (Mechanical and Physical Properties of Fibre Composites).

H. Lilholt, materialnyt No. 5 (1979) 29-40.

The basic mechanical and physical properties of fibre composites are presented in semiquantitative form. Typical fibres, glass, carbon and kevlar, and their properties are listed.

Fremstilling af fiberforstærkede vindmøllevinger. (Production of Fibre-Reinforced Rotor Blades for Wind Turbines).

Aa. Lystrup, materialnyt No. 5 (1979) 41-52.

The wind energy programme supported by the Danish Government includes the construction of two 630 kW wind turbines. The rotor which is 40 m in diameter consists of 3 blades. The blade is a hybrid component of steel and glass fibre reinforced polyester. The outer 12 m-section of the blade is entirely made of glass fibre reinforced polyester. A detailed description of the manufacturing of the outer section of the blade is given. The glass fibre reinforced polyester section of the blade consists of a filament wound D-

shaped spar and hand laid-up shells (air foils). The D-spar is filament wound from a 21 cm wide woven roving tape, which has 93% of its fibres oriented across the tape. The tape is wound around a steel mandrel in such a way that 93% of the fibres are oriented almost parallel to the axis of the spar. The shells are a hand laid-up sandwich construction with balsa wood as core material.

Thermoelasticity and Plasticity of Composite Materials.
O. Bøcker Pedersen, In: Mechanical Behaviour of Materials, Proceedings of the Third International Conference on Mechanical Behaviour of Materials, Cambridge, 20-24 August 1979. Vol. 3. Edited by K.J. Miller and R.F. Smith (Pergamon Press, Oxford, 1979) 263-273.

A mean field model for the thermoelastic deformation of two-phase composites is presented and compared with major previous formulations. The model can be combined with a continuum model for low-temperature plastic deformation to predict a new hardening contribution (the elastic mean stress) arising from elastic non-homogeneity. A preliminary application of the mean field model to the elastic-plastic deformation of copper with tungsten fibres is described.

Teorier om kompositters deformation. (Theories on the Deformation of Composites).
O. Bøcker Pedersen, materialnyt No. 5 (1979) 3-14.

Theories for the deformation of fibre composites under different conditions of temperature and stress are considered. Bounds are given for the thermoelastic moduli of polyester with glass fibres. The continuum model for low-temperature plastic deformation is described to explain the major hardening contributions in elastic-plastic fibre composites. Simple heuristic models for high-temperature deformation of fibre composites are discussed.

$SCl_3^+AlCl_4^-$: Improved Synthesis and Characterization.
G. Mamantov, R. Marassi, F.W. Poulsen, S.E. Springer, J.P. Wiaux, R. Huglen and N.R. Smyrl, J. Inorg. Nucl. Chem. 41 (1979) 260-261.

The electrooxidation of elemental sulfur in acidic chloroaluminate melts results in the formation of tetravalent sulfur. The resulting S(IV) solution shows promise as a cathode system in rechargeable high-energy batteries. This paper deals with the chemical preparation of a stable compound containing tetravalent sulfur and chlorine, $SCl_3^+AlCl_4^-$.

Characterization of Tantalum Pentachloride Containing Melts by Raman Spectroscopy.

R. Huglen, F.W. Poulsen, G. Mamantov and G.M. Begun, Inorg. Chem. 18 (1979) 2551-2555.

Raman spectroscopy has been used to obtain information on various $TaCl_5$ containing melts. In molten $TaCl_5$, studied between 220 and 350°C, a gradual dissociation of molecular $Ta_2Cl_{10}(D_{2h})$ to monomeric $TaCl_5(D_{3h})$ appears to take place. Evidence for a stable octahedral $TaCl_6$ ion in molten $KTaCl_6$ at 420°C is presented. The binary $TaCl_5$-$AlCl_3$ system at ~ 200°C contains noninteracting Ta_2Cl_{10} and Al_2Cl_6 molecules. The complexes formed when $TaCl_5$ is dissolved in $AlCl_3$-NaCl and $AlCl_3$-KCl melts depend on acidity and temperature: $TaCl_6(O_h)$ is present only in basic to slightly acidic melts; $TaCl_5(D_{3h})$ is mainly stable in neutral and acidic melts at high temperature; Ta_2Cl_{10} is found only in acidic melts at lower temperatures.

Cyclic Deformation of Copper Polycrystals.

K.V. Rasmussen and O. Bøcker Pedersen, In: Strength of Metals and Alloys, Proceedings of the 5th International Conference on Strength of Metals and Alloys, Aachen, 27-31 August 1979. Vol. 2. Edited by P. Haasen, V. Gerold and G. Kostorz (Pergamon Press, Oxford, 1979) 1219-1223.

Single crystals and polycrystals were cyclically deformed in tension-compression at constant low plastic strain amplitudes. The cyclic stress-strain curve of the polycrystals is similar to that of single crystals in the sense that it displays a plateau. In contrast to the single crystal plateau, however, the polycrystal plateau extends to a plastic strain amplitude of only ~ 10^{-3} at which the polycrystals are not completely covered by slip bands. A simple theoretical estimate shows that a small plastic shear strain (of the order of ~ 10^{-2}) in a (hypothetical) bulk wall structure can be elastically accommodated by the polycrystals.

A Positron Annihilation and Transmission Electron Microscopy Investigation into the Annealing of Copper after Neutron Irradiation at 250°C.

M. Eldrup, O.E. Mogensen, B.N. Singh and J.H. Evans, In: Positron Annihilation, Proceedings of the Fifth International Conference on Positron Annihilation, Lake Yamanaka, 8-11 April 1979. Edited by R.R. Hasiguti and K. Fujiwara (The Japan Institute of Metals, Aoba Aramaki, 1979) 711-715.

High purity copper was neutron irradiated to doses of 10^{18} and 5×10^{18} n/cm^2 at 250°C. The subsequent annealing behaviour was followed by positron lifetime and angular correlation measurements, and the damage structure was investigated by transmission electron microscopy (TEM). The as-irradiated samples contained voids (of the order 10^{14} cm^{-3}) and dislocations ($<3\times10^{9}$ cm/cm^3). None of the positron parameters showed clear annealing stages, but rather gradual changes with annealing temperature, viz. the trapped positron lifetime increased from about 225 psec to about 375 psec at 475°C, while its intensity decreased almost to zero. Also a trapped positron component in the angular correlation curves decreased with increasing annealing temperature. The voids seen by TEM were essentially unaffected up to 400°C, whereas complete annealing of the voids had taken place at 500°C. These results are discussed in terms of possible effects of dislocations, visible voids, and submicroscopic vacancy clusters stabilized by gas atoms. Also the role of impurities migrating to voids and small clusters is briefly mentioned.

A Theory for Void Nucleation and its Comparison with Experiments.

A.J.E. Foreman and B.N. Singh, In: Irradiation Behaviour of Metallic Materials for Fast Reactor Core Components, Proceedings of the International Conference on the Irradiation Behaviour of Metallic Materials for Fast Reactor Core Components, Ajaccio, 4-8 June 1979. Edited by J. Poirier and J.M. Dupouy (Le Commissariat a l'Energie Atomique, Gif-sur-Yvette, 1979) 113-121.

A tentative theory for void nucleation, based on the diffusion of gas atoms in vacancy clusters, is compared with the published data for pure metals and two steels. The temperature dependence of the void density shows activation energies characteristic of vacancy migration, in accord with the theory.

The Effect of Silicon on the Void Swelling of a "Pure" Austenitic Steel.

M.J. Makin, G.P. Walters, B.N. Singh and T. Leffers, In: Irradiation Behaviour of Metallic Materials for Fast Reactor Core Components, Proceedings of the International Conference on the Irradiation Behaviour of Metallic Materials for Fast Reactor Core Components, Ajaccio, 4-8 June 1979. Edited by J. Poirier and J.M. Dupouy (Le Commisariat a l'Energie Atomique, Gif-sur-Yvette, 1979) 195-203.

Results are reported on the effect of silicon additions up to 2 wt.% on the void swelling of a 'pure' Fe-15Cr-13Ni-1Mn alloy irradiated by 1 MeV electrons in an HVM over the temperature range 400-650°C. Data is given on the variation in void density, void size, linear swelling rate and threshold dose with silicon content.

Thermodynamics and Structure of Nonstoichiometric Binary Oxides.

O. Toft Sørensen, In: Phase Diagrams: Materials Science and Technology. Refractory Materials. Vol. 6-V. Edited by A.M. Alper (Academic Press, New York, 1978) 75-125.

In this publication the thermodynamic properties and defect structure of each of the three classes of non-stoichiometric oxides are reviewed:

(1) Essentially stoichiometric oxides with narrow composition ranges.
(2) Non-stoichiometric oxides with a limited composition range.
(3) Grossly non-stoichiometric oxides with broad composition ranges.

Interpretation of Quasi-Isothermal Thermogravimetric Weight Curves.

O. Toft Sørensen, Thermochim. Acta 29 (1979) 211-214.

The abstract appeared in the previous progress report p. 56.

Thermal Analysis of the Decomposition of Ammonium Uranyl Carbonate (AUC) in Different Atmospheres.

L. Hälldahl and O. Toft Sørensen, Thermochim. Acta 29 (1979) 253-259.

The abstract appeared in the previous progress report p. 56.

On Fatigue Reliability Under Random Loads.
R. Talreja, Eng. Fracture Mech. 11 (1979) 717-732.

We consider the problem of estimating the probability of survival (non-failure) and the probability of safe operation (strength greater than a limiting value) of structures subjected to random loads. These probabilities are formulated in terms of the probability distributions of the loads and the material strength. For the material strength, the Weibull distribution is assumed, the parameters of which are estimated by a statistical analysis of the experimental tensile strength of steel specimens subjected to different periods of random loads. The statistical analysis shows that, with the application of random loads, the initial homogeneous distribution of strength changes to a two-component distribution, reflecting the two-stage fatigue damage. In the crack initiation stage, the strength increases initially and then decreases, while an abrupt decrease of strength is seen in the crack propagation stage. The consequences of this behaviour on the fatigue reliability are discussed.

Fatigue Reliability Under Multiple-Amplitude Loads.
R. Talreja, Eng. Fracture Mech. 11 (1979) 839-849.

A method to determine the fatigue reliability of structures subjected to multiple-amplitude loads is presented. Unlike the more common cumulative damage methods, which are usually based on fatigue life data, the proposed method is based on tensile strength data. Assuming the Weibull distribution for the initial tensile strength and the fatigue life, the probability distributions for the residual tensile strength in both the crack initiation and the crack propagation stages of fatigue are determined. The method is illustrated for two-amplitude loads by means of experimental results obtained by testing specimens of a structural steel and is shown to be more accurate than the Palmgren-Miner cumulative damage method.

Laminatberegninger. (Laminate Analysis).
R. Talreja, materialnyt No. 5 (1979) 15-28.

Composite materials are used in structures mostly in the form of laminates. A stress analysis of composite laminates can be rationally based on the linear elastic theory for anisotropic materials. The fundamentals of this theory are reviewed and the constitutive equations for laminates, in which each lamina is an orthotropic material, are derived.

Estimation of Weibull Parameters for Composite Material Strength and Fatigue Life Data.

R. Talreja, DCAMM Report No. 168 (1979) 28 pp.

Two classical methods for estimation of Weibull parameters, namely, the moment estimation and the maximum likelihood estimation are reviewed. It is demonstrated that, assuming the location parameter to be zero, the errors made in estimating both the scale and the shape parameters by these methods increase linearly with the true value of the location parameter. An alternative method for Weibull parameter estimation is proposed. This method provides estimates for all three parameters when the shape parameter is close to one, and estimates the scale and the shape parameters more accurately than the other two methods for higher values of the shape parameter. Furthermore, unlike the other methods, this method is capable of separating the constituent components in a multi-component sample and estimating the parameters of each component. This property makes the method suitable for statistical analysis of composite material strength and fatigue life data.

Metalhydrider som varmelagringsmedium. (Metal Hydrides as a Medium for Heat Storage).

B. Vigeholm, A.F. Andresen, K. Videm, D. Lewis and T. Dahlgren, Report (1979) 78 pp.

Conditions in the Nordic countries for applying metal hydrides as storage media for excess- and solar heat are discussed. Low- and high-temperature hydrides and possible system concepts are considered. A brief survey of potentially available heat sources is given. It is concluded that metal hydrides are potentially useful storage media.

Energy Storage Based upon Metal-Hydrogen Systems.

B. Vigeholm, In: Research on Energy Storage at Risø National Laboratory, Risø-M-2191 (1979) 29-33.

Preliminary results of the magnesium-magnesium hydride work performed in the Metallurgy Department are given and the current programme is outlined.

Energilagring ved hjælp af metalhydrider. (Metal Hydrides as a Medium for Energy Storage).

B. Vigeholm, materialnyt No. 1 (1979) 76-84.

The paper gives a description of some general properties of metal hydrides including comparison with other energy storing media. Suggested and demonstrated applications are listed and some described in more detail, e.g. vehicular fuel storage, load-levelling storage and heat pump/heat storage.

LECTURES

Helium Balance In High Burn-Up Fuel Rods.

H. Carlsen, presented at a Workshop Meeting on Fission Product Release, Halden, 19-20 March 1979. (Transcript available, 11 pp.).

The term "fission gas" generally comprises only xenon and krypton. Helium is another gaseous constituent often ignored. It is formed both by ternary fission and by alpha-decay of ^{242}Cm. An attempt is made to explain approximately the amount of helium found after irradiation to burn-up levels about 2500 and 3800 GJ/kgU, respectively.

Destructive P.I.E. on 5 Rods Irradiated in the Garigliano BWR - Piercing and Metallography.

H. Carlsen, presented at a Technical Meeting on Post Irradiation Examinations, Brussels, 29 March 1979. (Not available).

Post-irradiation examination of five LWR oxide fuel rods from the Garigliano power station has been performed at the Risø National Laboratory. Four of the rods contained fuel with initially 0.82% to 3.2% Pu in natural uranium oxide, the fifth rod was enriched in uranium. The burn up level is estimated to 20 GWd/tMeO_2. Piercing showed that the rods were intact. Metallography did not indicate any potential failures.

A New, First-Principles FGR-Model, Theory and Verification.

H. Carlsen and N. Kjær-Pedersen, presented at a Workshop Meeting on Fission Product Release, Halden, 19-20 March 1979. (Transcript available, 4 pp.)

A fission gas release model was developed, based on first principles. Diffusional release may occur when the fission gas concentration in a fuel grain exceeds the barrier concentration in a certain surface layer of the grain. The barrier concentration is due to the resolution effect induced by fission fragments traversing the grain boundaries, and hence, depends on fission density as well as temperature through the diffusion coefficient. Gas release may also result from grain boundary sweeping and columnar grain growth. The model predicts fairly well the gas release from both medium and high burn-up fuel rods.

Influence of Surface Treatments on the Shear Strength of Brazed Joints in Inconel X-750.

J. Christensen, presented at the 3rd International Brazing and Soldering Conference, London, 29-31 October 1979. (Transcript available, 8 pp.).

This paper describes an investigation in which it is found that the shear strength of joints in Inconel X-750 nickel brazed in a getter atmosphere at 1025°C and a vacuum of only 10^{-2} torr, are equal to or better than the shear strength obtained on "untreated" specimens brazed at at least a 50°C higher brazing temperature and in a high vacuum of 10^{-5} torr or better. This agrees well with earlier results - ref. (1) - where a perfect wetting was found at exactly the same conditions.

Three Dimensional Sound Field Examination. A Computer Aided Scanning System.

H.E. Gundtoft and T. Nielsen, presented at the Ninth World Conference on Non-Destructive Testing, Melbourne, 18-23 November 1979. (Manuscript published as Risø-M-2181 (1979) 8 pp.).

Grain Boundary Phenomena during the Nucleation of Recrystallization.

A.R. Jones, presented at the ASM Materials Science Seminar on Grain Boundary Structure and Kinetics, Milwaukee, 15-16 September 1979. (Proceedings to be published).

The paper presents a review of the current state of knowledge concerning the mechanisms involved in the nucleation of recrystallization. Particular emphasis is given to the influence of grain boundaries on recrystallization behaviour. The applicability of the various nucleation models to materials of different stacking fault energy is also considered.

Derivation of a Generalized Failure Criterion From Inter-Ramp Using WAFER-3 Simulations.

N. Kjær-Pedersen, presented at the Enlarged Halden Programme Group Meeting on Fuel Performance Experiment and Evaluation, Hankø, 18-22 June 1979. (To be published as Risø-M-report).

The 20 Inter-ramp experiments have been simulated by means of the Danish LWR fuel performance code WAFER-3. It has been concluded from the simulations that, even though strain and fission product concentration may play a role in the clad failure mechanism (stress corrosion cracking), the experimental failure observations are best correlated by means of a pure stress-time relationship. An analytical failure criterion, expressing time-to-failure in terms of calculated, average contact pressure during the hold-time, has been developed and generalized for use with water reactor fuel in a wider context.

Fission Gas Release in Ramp Testing.

P. Knudsen, presented at the Enlarged Halden Programme Group Meeting on Fuel Performance Experiment and Evaluation, Hankø, 18-22 June 1979. (Transcript available, 4 pp.).

Fission gas release determinations are presented for seven fuel pins ramp tested at burnup levels up to 27 GWD/tUO_2. Releases up to about 40% were observed after several weeks' hold time at 450 W/cm overpower level. Hold times less than 1 hour at higher power levels resulted in significantly lower releases.

Evaluation of Cladding Integrity of Ramp Tested UO_2-Zr Fuel Pins.

P. Knudsen and C. Bagger, presented at the IAEA Specialists' Meeting on Power Ramping and Power Cycling of Water Reactor Fuel and Its Significance to Fuel Behaviour, Arles, 14-18 May 1979. (Transcript available, 6 pp.).

Ramp testing of six PWR type fuel pins resulted in four failures. Nondestructive and destructive observations are compared and used to evaluate the cladding integrity of the individual fuel pins.

Destructive P.I.E. on 5 Rods Irradiated in the Garigliano BWR - Isotope Analysis.

N.R. Larsen, presented at a Technical Meeting on Post Irradiation Examination, Brussels, 29 March 1979. (Not available).

The paper presents the results from the quantitative analysis of uranium, plutonium, americium, and curium isotopes, together with burn-up analysis by the ^{148}Nd method, in 16 samples from Pu enriched UO_2 fuel, irradiated to about 1900 GJ/kgU.

Fibre til armering af plast. (Fibres for Reinforcement of Plastics).

H. Lilholt, presented at the Scandinavian Plastics Conference, Copenhagen, 4 April 1979. (Not available).

Typical fibres for reinforcement of plastics are presented. Their structure, fabrication and properties are described. The fibres are glass, carbon, kevlar, boron and aluminium oxide.

Brudforhold i fiberforstærkede materialer. (Fracture Behaviour of Fibre-Reinforced Materials).

H. Lilholt, presented at Dansk Selskab for Materialprøvning og -forskning's Meeting on Fracture Mechanics, Lyngby, 24 April 1979. (Manuscript published in materialnyt No. 2 (1979) 61-71).

Mekaniske og fysiske egenskaber af fiberkompositter. (Mechanical and Physical Properties of Fibre Composites).

H. Lilholt, presented at Dansk Selskab for Materialprøvning og -forskning's Meeting on Fibre-Reinforced Materials, Lyngby, 19 September 1979. (Manuscript published in Materialnyt No. 5 (1979) 29-40).

Fremstilling af fiberforstærkede vindmøllevinger. (Production of Fibre-Reinforced Rotor Blades for Wind Turbines).

Aa. Lystrup, presented at Dansk Selskab for Materialprøvning og -forskning's Meeting on Fibre-Reinforced Materials, Lyngby, 19 September 1979. (Manuscript published in materialnyt No. 5 (1979) 41-52).

Probabilistic Assessment of Light Water Reactor Fuel Performance.

I. Misfeldt, held at the Technical University of Denmark, Lyngby, 9 October 1979. (Published as Risø Report No. 390 (1978) 64 pp.).

A computer system for the statistical evaluation of LWR fuel performance has been developed. The computer code FRP, Fuel Reliability Predictor, calculates the distributions for parameters characterizing the fuel performance and failure probability. The statistical methods employed are either Monte Carlo simulations or a low order Taylor approximation. Included in the computer system is a deterministic fuel performance code, which has been verified by comparison with data from irradiation experiments. The distributions for all material data utilized in the fuel simulations are estimations from the best available information in the literature. For the failure prediction, a stress corrosion failure criterion has been derived. The failure criterion is based on data from out-of-reactor stress corrosion experiments performed on unirradiated and irradiated zircaloy with iodine present.

Teorier om kompositters deformation. (Theories on the Deformation of Composites).

O. Bøcker Pedersen, presented at Dansk Selskab for Materialprøvning og -forskning's Meeting on Fibre-Reinforced Materials, Lyngby, 19 September 1979. (Manuscript published in materialnyt No. 5 (1979) 3-14).

Hard and Soft Ionic Interactions and other Concepts of Solution Chemistry applied to the Solid State.

F.W. Poulsen, presented to Dansk fysisk Selskab, Risø, 20 March 1979. (Not available).

It is well known, to chemists, that hard ions in solution prefer other hard ions in complex formation, and similarly do soft ions prefer other soft ions. This is the so-called dual rule of Pearson. The crucial point is how to define scales of softness for ions. This work takes molar refractivity of ions, which in turn are proportional to ionic polarizability, as a measure of softness. Some general structure-independent trends are revealed when anion and cation solid electrolytes are classified according to this scale of softness. Complex formation in the solid solution series $MO-ZrO_2$ and $M_2O_3-ZrO_2$ is treated qualitatively.

Behaviour of Hard and Soft Ions in Solid Electrolytes.
F.W. Poulsen, poster presented at the NATO Advanced Study Institute on Materials for Advanced Batteries, Aussois, 9-14 September 1979. (Proceedings to be published).

The concept of polarizability is frequently referred to in qualitative descriptions of superionic conductors. A high polarizability of the diffusing ion, as for the soft silver ion, is considered essential. This paper treats some of the problems involved in defining a consistent scale of polarizabilities and the possible use of such a tool. The general trend revealed can be formulated:

Cation conduction in solids is favoured, when the cation is harder than the immobile lattice. Anion conduction is favoured when the anion is harder than the immobile lattice.

Composite Lithium-Iodide/Aluminium-Oxide Solid Electrolytes.
F.W. Poulsen and O. Toft Sørensen, presented at the EUCHEM Conference on Solid State Chemistry and Electrochemistry, especially with Respect to its Application in Battery Research, Endorf, 1-5 May 1979. (Not available).

LiI-Al_2O_3 solid electrolytes are presently used in long-life pacemaker batteries. The ionic conductivity of these solid electrolytes has been shown to depend strongly on the fabrication route. Two models explaining possible conductivity enhancement in composite electrolytes are discussed. Results obtained at Risø reveal the influence of crystal water on the conductivity.

Phase Relationships and Defects in Non-Stoichiometric Oxides.
O. Toft Sørensen, 4 lectures held at Norges tekniske Højskole, Trondheim, 1-2 March 1979. (Transcript available, 50 pp.).

In the lecture the following topics were covered:

(1) General considerations of non-stoichiometric phases: Types of non-stoichiometric oxides and their defect structure
(2) Thermodynamics
(3) Techniques for examination of non-stoichiometric oxide systems
(4) Thermodynamics and structure of CeO_{2-x}
(5) Oxygen ion conductors.

Defect Structure of Substoichiometric Oxide Systems.

O. Toft Sørensen, held at A.E.R.E., Harwell, 8 March 1979. (Not available).

A model of the defect structure for substoichiometric fluorite oxides was discussed. In this model the structure of the ordered phases observed for instance in the CeO_{2-x} system is described by a systematic packing of three types of defect complexes consisting of respectively 22, 18 and 6 cation tetrahedra surrounding the cation tetrahedron containing the defect (oxygen vacancy).

Model of the Thermodynamic Properties and Structure of the Non-Stoichiometric Plutonium and Cerium Oxides.

L. Manes, O. Toft Sørensen, C. Mari and I. Ray, presented at the International Symposium on Thermodynamics of Nuclear Materials, Jülich, 29 January to 2 February 1979. (Proceedings to be published).

The tetrahedral defect consisting of one oxygen vacancy bonded to two reduced cations - a $V_O^{\cdot\cdot},2(Me^{3+})'$ unit - is an important concept, which, as shown in the present work, can explain both the thermodynamic properties and the structures of the phases of the PuO_{2-x} and CeO_{2-x} systems. Based on this concept a statistical thermodynamic model has been developed and this model is described along with some preliminary calculations. A relatively good agreement with experimental thermodynamic data was obtained in this calculation. Using the exclusion principle, defect complexes each containing one tetrahedral defect are derived and it is shown that a systematic packing of these gives a good description both of the non-stoichiometric and the ordered phases observed for these oxide systems.

Laminatberegninger. (Laminate Analysis).

R. Talreja, presented at Dansk Selskab for Materialprøvning og -forskning's Meeting on Fibre-Reinforced Materials, Lyngby, 19 September 1979. (Manuscript published in materialnyt No. 5 (1979) 15-28).

Energilargring ved hjælp af metalhydrider. (Metal Hydrides as a Medium for Energy Storage).

B. Vigeholm, presented at Dansk Selskab for Materialprøvning og -forskning's Meeting on Energy Storage, Lyngby, 19 March 1979. (Not available).

The general concept of metal hydrides was explained and some properties related to energy storage given. Applications in land transportation and load levelling in power plants were explained. The heat associated with the hydrogen storage was demonstrated as an alternative means of energy storage application. Also heat pump action of the hydride system was explained.

Energilagring med metalhydrider. (Metal Hydrides as a Medium for Energy Storage).

B. Vigeholm, presented at Nordjysk Energimesse, Brønderslev, 20 April 1979. (Not available).

The lecture gave the present status of hydride research emphasizing the energy storage applications. Some of these were described more thoroughly and possible implications to the national energy supply discussed.

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